NAVORD REPORT 95-46

COPY NO. 28

PHOTOGRAPHY OF UNDERWATER EXPLOSIONS II

HIGH SPEED PHOTOGRAPHS OF BUBBLE PHENOMENA

A BUREAU OF ORDNANCE PUBLICATION 17 DECEMBER 1946

NAVY DEPARTMENT
BUREAU OF ORDNANCE
WASHINGTON, D. C.

Vice Admiral G. F. Hussey, Jr., USN
Chief of the Bureau of Ordnance

Captain K. H. Noble, USN
Director, Research and
Development Division

Captain S. H. Crittenden, Jr., USN
Ammunition and Explosives

Dr. Stephen Brunauer
High Explosives and
Amphibious Munitions

NAVORD Report 95-46

PHOTOGRAPHY OF UNDERWATER EXPLOSIONS II
HIGH SPEED PHOTOGRAPHS OF BUBBLE PHENOMENA

by

E. Swift, Jr., P. M. Fye, J. C. Decius, and R. S. Price

UNDERWATER EXPLOSIVES RESEARCH LABORATORY
WOODS HOLE OCEANOGRAPHIC INSTITUTION
WOODS HOLE, MASSACHUSETTS

17 December 1946

NAVY DEPARTMENT
BUREAU OF ORDNANCE
WASHINGTON, D. C.

NAVORD Report 95-46 17 December 1946

PHOTOGRAPHY OF UNDERWATER EXPLOSIONS II HIGH SPEED PHOTOGRAPHS OF BUBBLE PHENOMENA

1. NavOrd Report 95-46 describes the techniques for making underwater photographs of the bubble arising for an underwater explosion. It includes examples of such photographs taken at depths ranging from 200 - 700 ft. in the open sea and also photographs taken near the surface.

2. The report presents the interpretations of the authors and does not necessarily represent the views of the Bureau of Ordnance.

3. This report does not supersede any existing publication of the Bureau of Ordnance.

G. F. HUSSEY, Jr.
Vice Admiral, U. S. Navy
Chief of the Bureau of Ordnance

, Captain, U. S. Navy
Asst Director, Research and
Development Division
By direction

CONTENTS

LIST OF FIGURES

ABSTRACT

The techniques developed recently at the Underwater Explosives Research Laboratory for photographing underwater explosions in the open ocean are described. High speed motion pictures of explosion product bubbles from 1 oz and $\frac{1}{2}$ lb charges of various explosives are shown. These pictures were taken at depths ranging from 200-700 ft. The oscillation of the bubble can be followed through several periods, and various details observed such as the rate of bubble growth, maximum bubble radius, surface irregularities on the bubble and the effect of charge shape and casing.

High speed motion pictures are also shown of charges close to the surface of the water. Migration of the bubble, its interaction with the water surface and the appearance of cavitation bubbles are demonstrated.

I. INTRODUCTION

This report presents the techniques developed at UERL since September 1945 for the motion picture photography of underwater explosion phenomena in the open ocean, and shows a number of the photographs obtained. The problems involved in this work have been overcome to the extent that at present open water shooting may be regarded as a practicable and important technique for the study of underwater explosions. Most of the work reported here was done at NOB Guantanamo Bay, Cuba, on the research vessel "Atlantis".

A number of advantages are secured by using the ocean instead of a tank. The size of charge studied is not as limited--photographs of full scale weapons have been obtained. The complications due to walls are eliminated. A wide variation in hydrostatic pressure can be used--photographs have been taken at depths from 1-700 ft, and unquestionably this range can be extended.

The principal limitations are the lack of suitable reference points in the photographs, and the relatively low transparency of the water in many locations. The first problem has been solved in part by mounting the charge, camera and associated equipment on a rigid framework. The behavior of small charges (½ lb) relative to the framework can then be observed. No such arrangement is feasible for large charges.

Water sufficiently clear for satisfactory photographs is not often found over the continental shelf of the eastern United States. However, clear water is relatively close to shore off Florida, in the Bahamas and near Cuba. Further off shore, the water is usually very clear. In a location two miles off Guantanamo Bay, photographs were taken at distances up to 100 ft. Very sharp photographs were obtained at camera-to-charge distances of 30-40 ft. The limiting distance for good photography seemed to be about 80 ft in this water, which had a Secchi disc reading of 160 ft.1/

Three different cameras were used--the Eastman High-Speed Camera and the Jerome Camera which are described in Ref. 1, and a 35-mm Fastax Wide Angle Camera, described below. The Jerome Camera was used at a speed of 40-45 frames/sec and the other two cameras at about 2000-2500 frames/sec. In addition, motion pictures of the surface of the water were taken from the deck using a Mitchell 35-mm camera and an Eastman ciné special 16-mm camera.

Studies were made of the appearance and size of explosion product bubbles at various depths. Half-pound charges of several explosives were compared and the effect of charge shape

---

1/ Photography of Underwater Explosions, by P. M. Fye, R. W. Spitzer, and J. E. Eldridge, OSRD 6246, NDRC A-368, p. 2. The Secchi disc reading is the depth at which an 8 in. white disc just disappears from view, and is a measure of the transparency of the water.

and casing on the bubble investigated in a preliminary manner. Migration of bubbles from 25 gm charges near the free surface of the ocean and also near structures was studied. Photographs of the nature of the damage process using scale models were made. A few photographs of 300 lb depth charges and of 56 lb demolition blocks were taken in which the behavior of the bubble can be clearly seen. The underwater trajectory of depth bombs dropped from a plane has been photographed.

The results reported here are purely qualitative; a detailed study of the quantitative aspects of the data will be presented later. In general, the results obtained so far are quite incomplete and indicate the tremendous amount of work that should be done in this field.

II. METHODS

1. Eastman High-Speed Camera

No important modifications since the last report (Ref. 1) were made in the use of this camera. The second type of stuffing box for the electrical cables has been adopted, since it (Fig. 142, ibid) was found to be satisfactory at all depths, the simpler type (Fig. 141, ibid) having given some trouble. The power and timer plugs have been moved to the front of the camera for convenience.

Excellent photographs of the behavior of 1 oz charge bubbles (Fig. 1) and of the damage process for cylindrical models (Fig. 2) were made using front lighting with a white background to silhouette the object. Details of the set-up are shown in Ref. 1, Figs. 15 and 16 and Ref. 2, Fig. 8.

Four No. 31, GE Photoflash bulbs placed in one explosion proof case were set off simultaneously nine ft from the charge. Under these conditions an adequate exposure was made at f/2.7 and 2000-2500 frames/sec. The film used was Super-XX Panchromatic Negative (found more satisfactory than Reversible) and by using double the normal developing time in D-76 a reasonably contrasty negative was obtained. Focusing was done by gound glass in air, taking a distance in air 3/4 of the object distance under water.

2. 35-mm Fastax Wide Angle Camera and Associated Equipment

This camera, manufactured by the Western Electric Company, has a 39° maximum angle of view with a 1.5 in. focal length lens on 35-mm film and runs at speeds from 600-3600 frames/sec. The wide angle of view and the large image make the camera suitable for photographs of $\frac{1}{2}$ lb charges at a practicable underwater

2/ Damage to Thin-Steel Cylindrical Shells by Underwater Explosions. II, by J. C. Decius, G. Gever, NavOrd Report No. 106-46.

Fig. 1. Explosion product bubble from 1 oz tetryl at 400 ft.

Fig. 2. Cylindrical model at 400 ft. Charge outside field of view.

Fig. 3. Cylindrical model and bubble at 600 ft.

Fig. 4. Cylindrical model and bubble near surface.

working distance of 30 ft. The long rectangular shape of the field (each Fastax frame full width and half height of standard 35-mm frame) permitted simultaneous pictures of D cylinders (see Ref. 2 for nomenclature) and explosion product bubbles (Fig. 3), and also of SD cylinders, bubbles, and the water surface (Fig. 4).

Photographs have been taken at speeds from 1250 up to 2800 frames/sec at depths ranging to 700 ft. Using eight No. 31 photoflash bulbs at a distance of 9 ft from the object, adequate exposures were obtained on Super-XX film at f/2.7 and 2500 frames/sec. It was found necessary to give the film 2 times normal development in D-76 to get satisfactory contrast.

The explosion proof steel case for the Fastax camera (Fig. 5) is structurally similar to that for the Eastman camera (Fig. 13, Ref. 1). The twelve bolt holes in the ends of the case are spaced 30° apart to permit the case, camera, and hence the field of view, to be rotated through exactly 90° using only one set of bolt holes on the rig. To avoid the necessity for a unique orientation of the lid, the camera was not aimed through it, but through a hole in the solid end of the case, which was of such a diameter that the lens protruding into it had ample clearance. The window on the outside of the hole was made of 1 in. thick lucite and held by a brass collar as shown in the figure. This oversize window allowed an ample field of view for the wide angle lens and was large enough so that any distortion of the lucite caused by the collar would be outside the field of view. A thin layer of gasket sealer[3] was used under the window which was flush against the case. No leakage here was observed even at 1000 ft.

Two longitudinal shock mount tracks were screwed to the inside of the case with through screws, the outer ends of which were sealed over with solder. Slides running in the tracks were fastened to the camera by a total of four #10 Lord shock mounts[4]. Movement of the slides along the tracks was prevented by screw stops, thus obviating the shock mounts on the ends of the cases necessary with the other cameras.

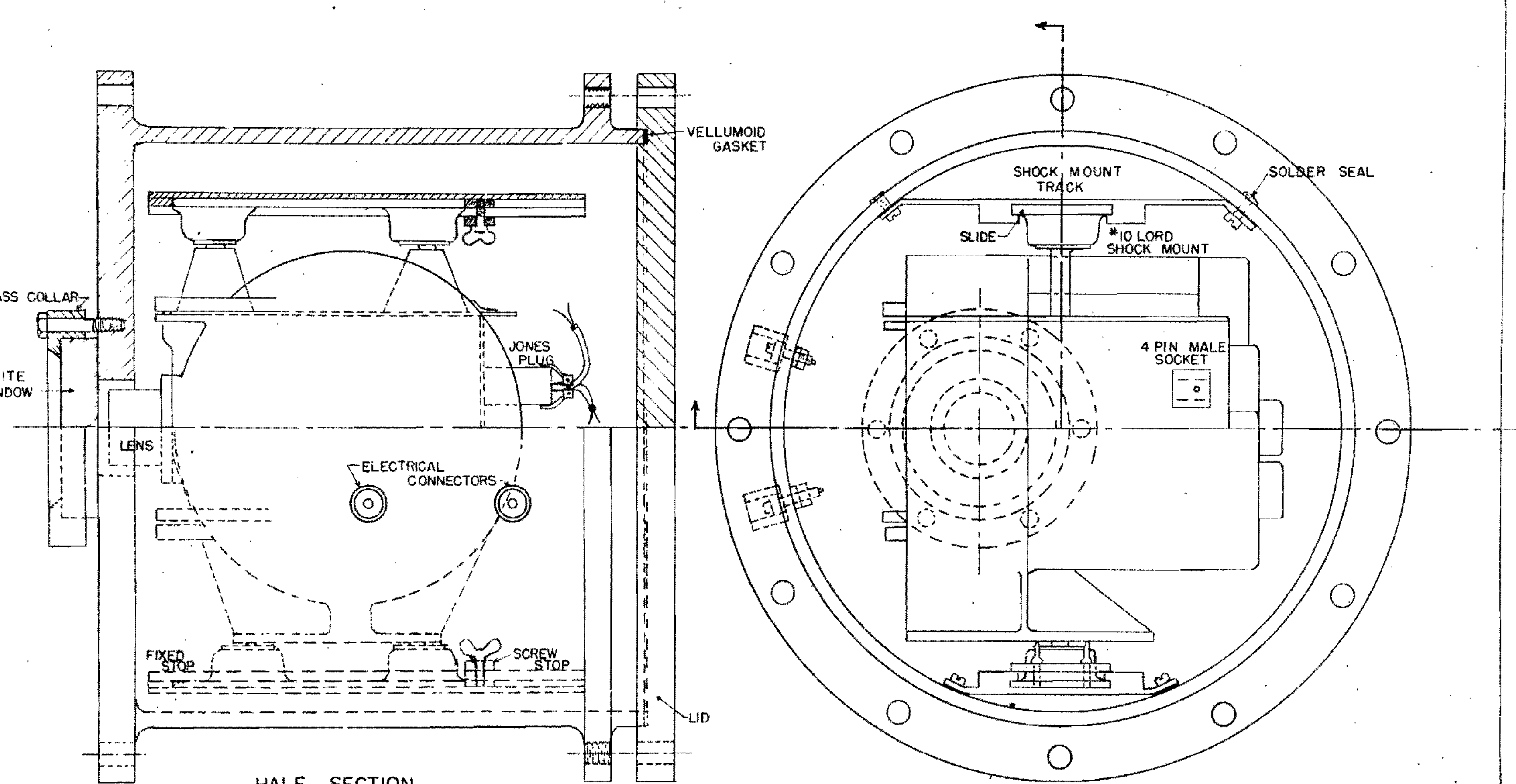
Four electrical connectors (Ref. 1, Fig. 142) spaced 4 in. apart were used to bring the timing signal and power into the case. Two short cords ending in a Jones plug[5] were fastened to the inside ends of the connectors. This was plugged into a

---

[3] "Gasket Goo #2", Pep Manufacturing Company, New York, N. Y.

[4] Lord Manufacturing Company, Erie, Pennsylvania.

[5] Series 400; 4 prong plug. H. B. Jones Company, Chicago, Ill.



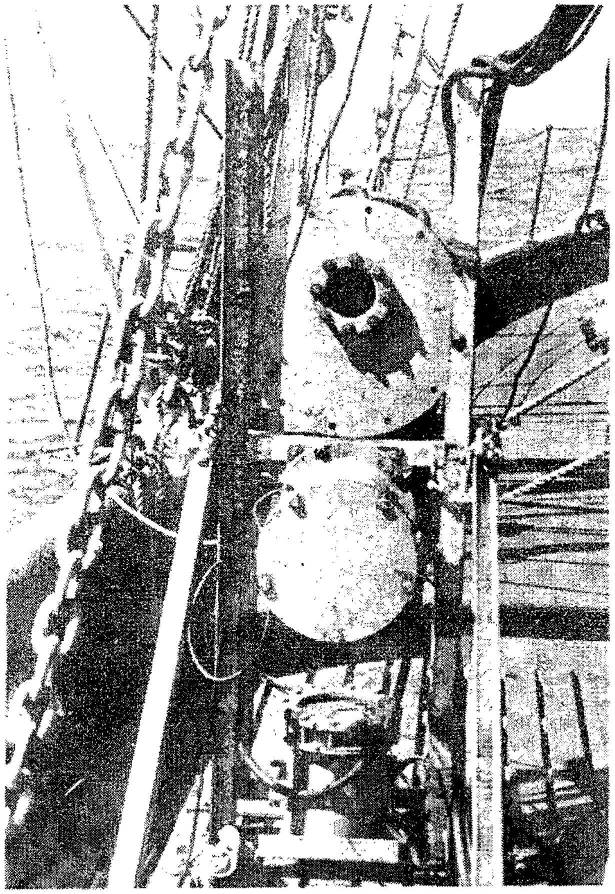
HALF SECTION
(SHOWING CAMERA IN PLACE)

END VIEW
(PLUG, LID AND UPPER SCREW STOP REMOVED)

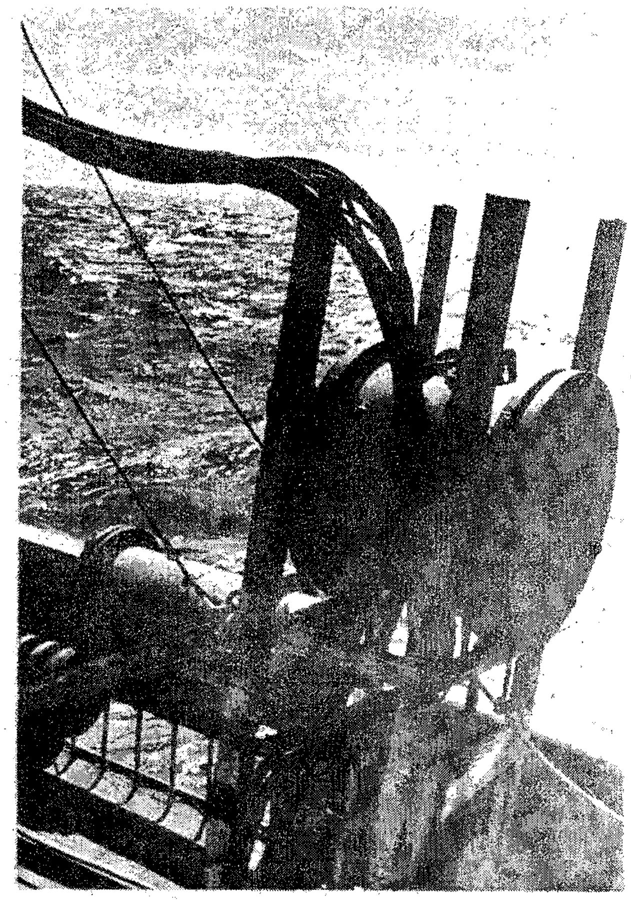
SCALE 0" 1" 2" 3" 4"

FIG. 5
EXPLOSION PROOF CASE
FOR
FASTAX CAMERA
UERL WOODS HOLE, MASS.

TRACED BY HRC
8-1-46



Front view



Side view

Fig. 6. Camera case for Fastax Camera mounted on rig. The Bourdon Depth Gauge case is below and in front of the camera case. The firing battery case is beneath the camera case.

single four pin socket on the camera after it had been inserted in the case.

The rigid framework on which the camera and charge plus auxiliary equipment were mounted was designed to allow a variety of arrangements of charge, camera, illumination, background and cylinder. The drawing (Fig. 7) shows a combination of parts used for many of the deep free bubble pictures. This rig weighs more than half a ton, and is about 35 ft in overall length.

The rig was suspended by a $\frac{1}{4}$ in. steel cable which was attached to a ring about 14 ft above the base. The wire and chain guys from the ring to the rig and the adjustment points are shown in Fig. 7. While in port before shooting, the rig was balanced and leveled in air by moving shackles from link to link in the chains.

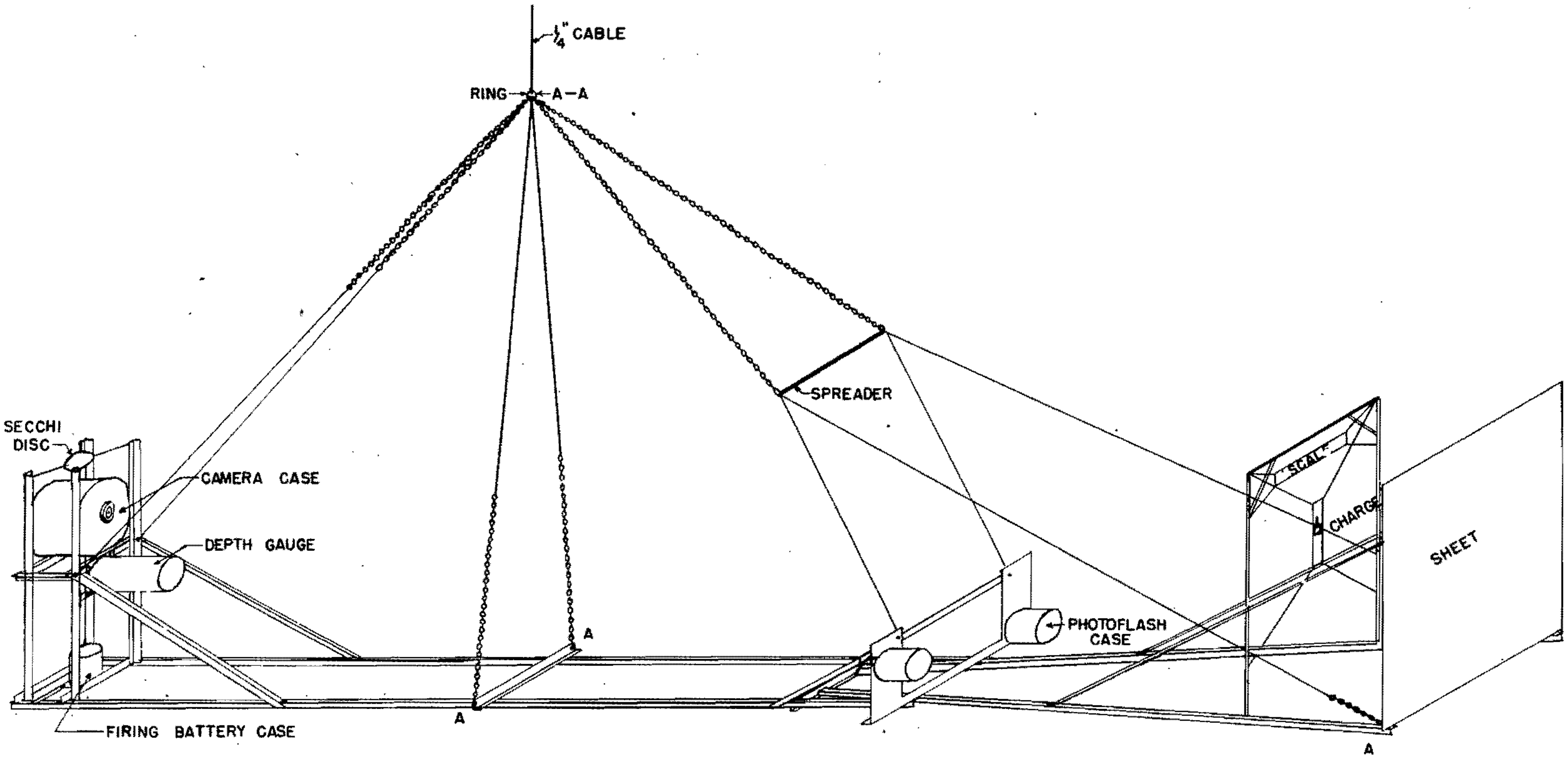
The most satisfactory photographic background was a white cotton bed sheet sewn to an iron rod frame. This sheet was found to have no effect on the bubble period when loosely hung about 3-4 ft from a $\frac{1}{2}$ lb charge. In a few cases a white painted galvanized iron sheet was used.

For remote operation three two-conductor electrical cables were run from the surface to the rig. Since the Fastax camera does not have a built-in firing switch like the Eastman High-Speed camera, it was necessary to fire from the surface. In order to fire the charge automatically when the camera had reached maximum speed and the photoflash bulbs were near peak intensity, and to turn off the camera, the firing circuit and camera power circuit were combined as shown in Fig. 8.

A typical operation would be as follows: when the safety switch is thrown and the firing button on the "Time-O-Lite"[6] is pressed, a 110 volt current is transmitted to the camera power relay and trips the electronic time delay (time delay gain changer, Appendix I). The camera then starts and is up to speed in a little more than a second. At 1.5 sec the time delay gain changer closes an internal relay which transmits the 110 volt AC power to the firing relay on the rig. This fires the flashbulbs and the charge, the latter being delayed a few milliseconds by a series resistor so that the bulbs can be at maximum brilliance when detonation occurs. After 3 sec the Time-O-Lite turns off the power to the camera relay, thus stopping the camera after the film has run through. Such a sequence of events is shown in Fig. 9. The times indicated here may easily be changed to suit other conditions by setting the dials on the instruments to the desired values.

The timing circuit used to mark the film at millisecond intervals is not shown in Fig. 8 since it is identical with that used with the Eastman High-Speed camera and is described in Ref. 1, Appendix III. The Fastax camera comes equipped with

[6] "Time-O-Lite" Master Model M-49, Industrial Timer Corporation, Newark, New Jersey.

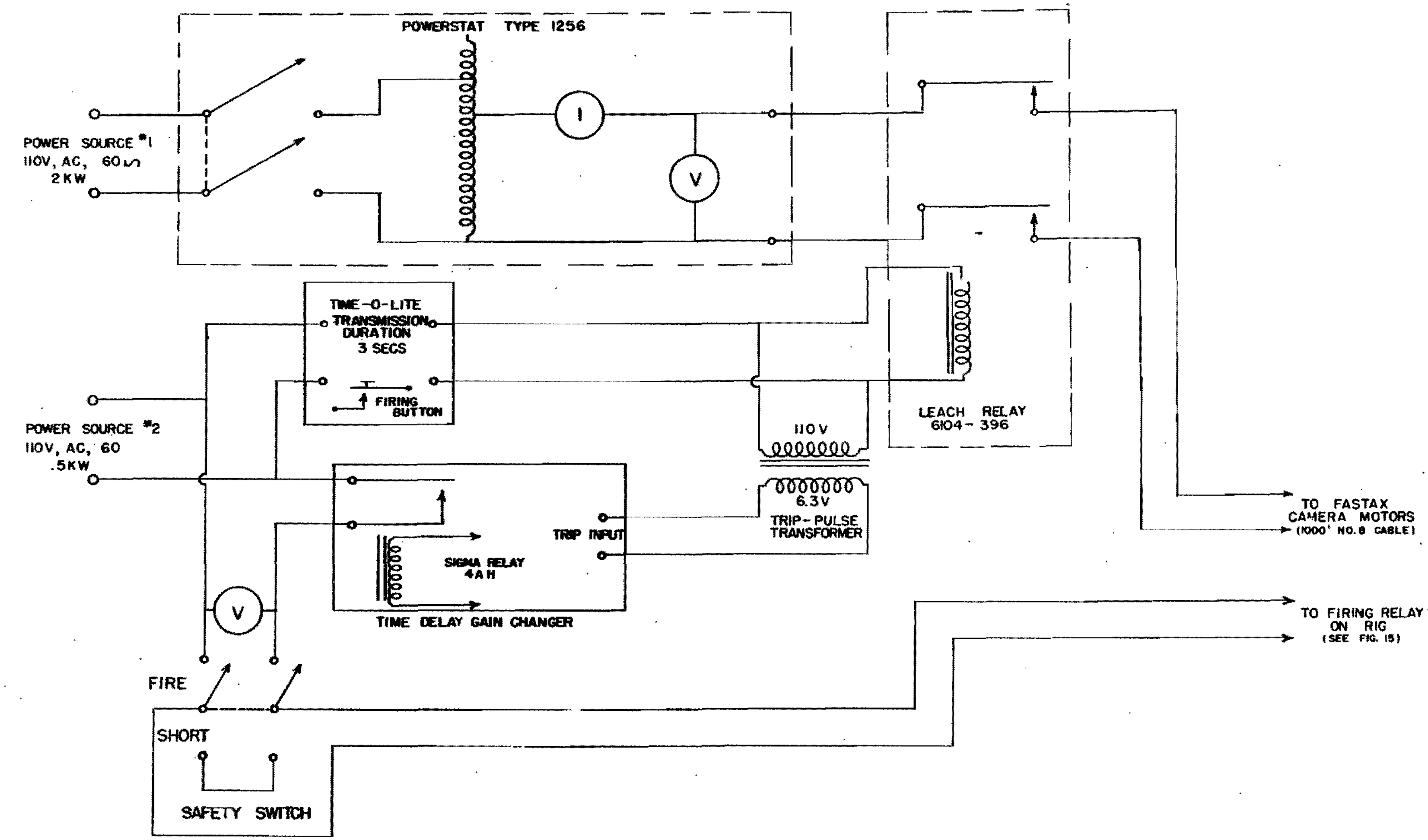


NOTES

PHOTOFLASH CASES FOCUSED ON CHARGE BY MEANS OF WASHERS
A- ADJUSTMENT POINTS FOR BALANCING RIG

TRACED BY HRC
7-31-46

FIG. 7
RIG FOR FASTAX CAMERA
UERL WOODS HOLE, MASS.



TRACED BY HRC
8-20-46

FIG. 8
CAMERA POWER AND FIRING DELAY CONTROLS
FOR
FASTAX CAMERA
UERL WOODS HOLE, MASS.

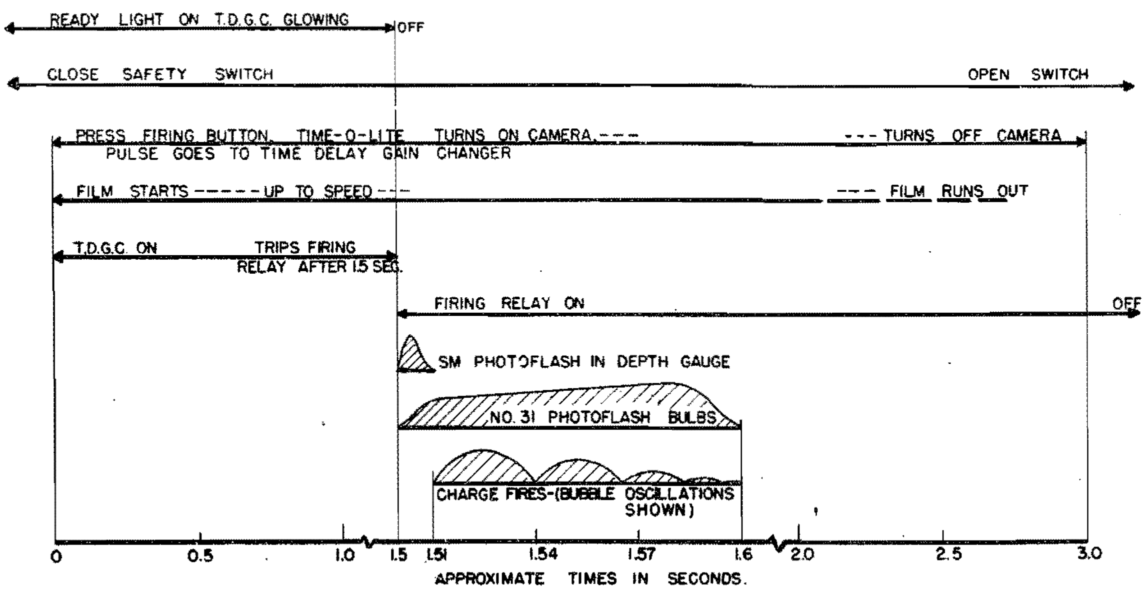


FIG. 9
AUTOMATIC FIRING SEQUENCE
FOR
FASTAX CAMERA
UERL WOODS HOLE, MASS.

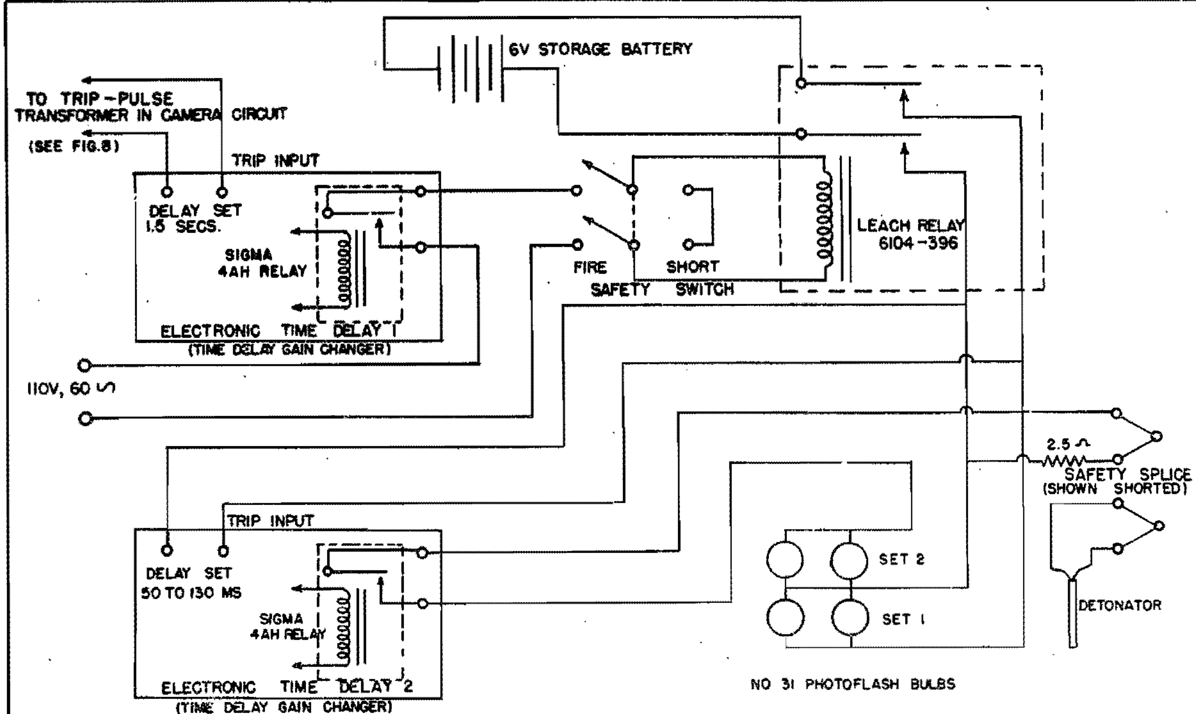


FIG. 10
SEQUENCE FIRING CIRCUIT
FOR
TWO SETS OF FLASHBULBS
UERL WOODS HOLE, MASS.

TRACED BY HRC
8-22-46

an AR-3 argon film-marking bulb which must be replaced by a GE Ne-48 neon bulb and corresponding socket to adapt it to this circuit.

In some of the shallow shots (less than 10 ft below the surface) two sets of photoflash bulbs were fired in sequence 50-90 msec apart to increase the total time of exposure. The circuit used for this is shown in Fig. 10.

3. Jerome 35-mm Camera

This camera with its short focus lens (1 in.) and wide angle of view can be used to photograph full scale phenomena. A number of underwater pictures of 56 lb and 300 lb TNT charges and of dropped bombs have been taken. These will be discussed in a forthcoming NavOrd report. (96-46.)

4. Depth Measurement

(a) Measured cable. It is necessary for bubble energy calculations to have an accurate value of the depth at which the explosion takes place. In the earlier work, depth was found from the length of steel cable paid out, multiplied by the cosine of the angle the cable made with the vertical at the surface to correct to actual depth. The assumption that the cable lies in a straight line from the surface to the apparatus is only an approximation and will introduce considerable error at the greater depths and angles.

The cable was let out over a wheel one meter in circumference, and the number of revolutions of this wheel were registered on a counter. The wheel was checked and found to be correct within 1%. Comparison of depths obtained from the corrected meter wheel reading and by other means indicate that for small wire angles (less than 10° from the vertical) the meter wheel reading is probably reliable to 2%. For larger angles up to 30°, the probable error is closer to 5%. Because of this discrepancy, it was felt necessary to develop a more accurate and reliable method of depth measurement.

(b) Bubble period. Using the 5/6 power law[7] the depth at which a detonation takes place can be calculated from the bubble period. A special charge which has been standardized for depth determination could be fastened to the rig, and the bubble period of this charge measured when the apparatus is in position for firing. Various measurements have indicated that the 5/6 power law holds to 1%, but the necessary standardization has not been done. Moreover, occasional large deviations appear in the measured periods, so it seems better at the present not to rely on this method until considerable further work has been done.

7/Theory of the Pulsations of the Gas Bubble Produced by an Underwater Explosion, by Conyers Herring. NDRC Report C4-Sr20-010.

(c) Bourdon depth gauge. A gauge was developed which automatically records static pressure, and therefore depth, at the moment of detonation by taking a flash bulb illuminated photograph of a calibrated Bourdon dial gauge. The apparatus is enclosed in a waterproof case bolted to the rig, the interior of the Bourdon tube being open to the water pressure at that depth. This gauge has proven accurate and is being modified to increase convenience in use.

(i) Construction. The Bourdon Depth Gauge shown in Figs. 11 and 12a consisted of a brass bed plate (A), fitted with rather yielding shock mounts, upon which was mounted a dial pressure gauge (B)8/ and a small cut film camera (C) (Ref. 1, Fig. 4 shows this camera in another case). The camera was focused upon the gauge face and recorded the gauge needle position at the instant an SM photoflash bulb (D) was fired by an external 6-volt DC source. A doorbell buzzer (E) attached to the back of the pressure gauge case, provided with its own dry cell voltage supply (F) and switch (G), was used to reduce sticking of the gauge mechanism. The external pressure was conducted to the gauge through a 4 ft coil of 1/16 in. copper tubing (H), which somewhat damped rapid pressure fluctuations and reduced the effect of the explosive shock on the gauge mechanism. The camera shutter trip was actuated by a solenoid (J) from an external 18-volt DC source. The whole unit was suspended by the four shock mounts (K) in a cylindrical watertight steel pressure case 20 in. long by 7 in. diameter and could be removed readily. The case was fitted with a vent (L) giving the gauge access to the external pressure, and the necessary electrical connectors (M), (Ref. 1, Fig. 142).

The right hand end of the case was free of internal connections (Fig. 11) and could be taken off to facilitate replacement of the flash bulb and to enable the operator to remove the camera between shots. A small brass clip, arranged to hold a card on which an identification number could be written, was placed immediately in front of the gauge face so that the shot number was recorded at the same time as the pressure (Fig. 12).

(ii) Operation. A calibrated dial gauge of range appropriate for the expected depth was used: 0-200 lb for depths to 400 ft, 0-400 lb for depths between 400 ft and 800 ft and 0-600 lb for depths from 800 ft to 1200 ft. In use the camera was loaded with Contrast Process Ortho cut film, the stop set at f/18 and the shutter set on "time". A fresh flash bulb was inserted, the buzzer turned on and the case sealed. The solenoid was then actuated once to open the camera shutter and the apparatus lowered. The short duration SM flash bulb was in parallel with the No. 31 flash bulbs used as illumination for the motion pictures so that the exposure was started 5-10 msec before detonation of the charge and was essentially

8/Heavy duty precision gauge, Type AAC-10853, Crosby Steam Gage & Valve Company, Boston, Massachusetts.

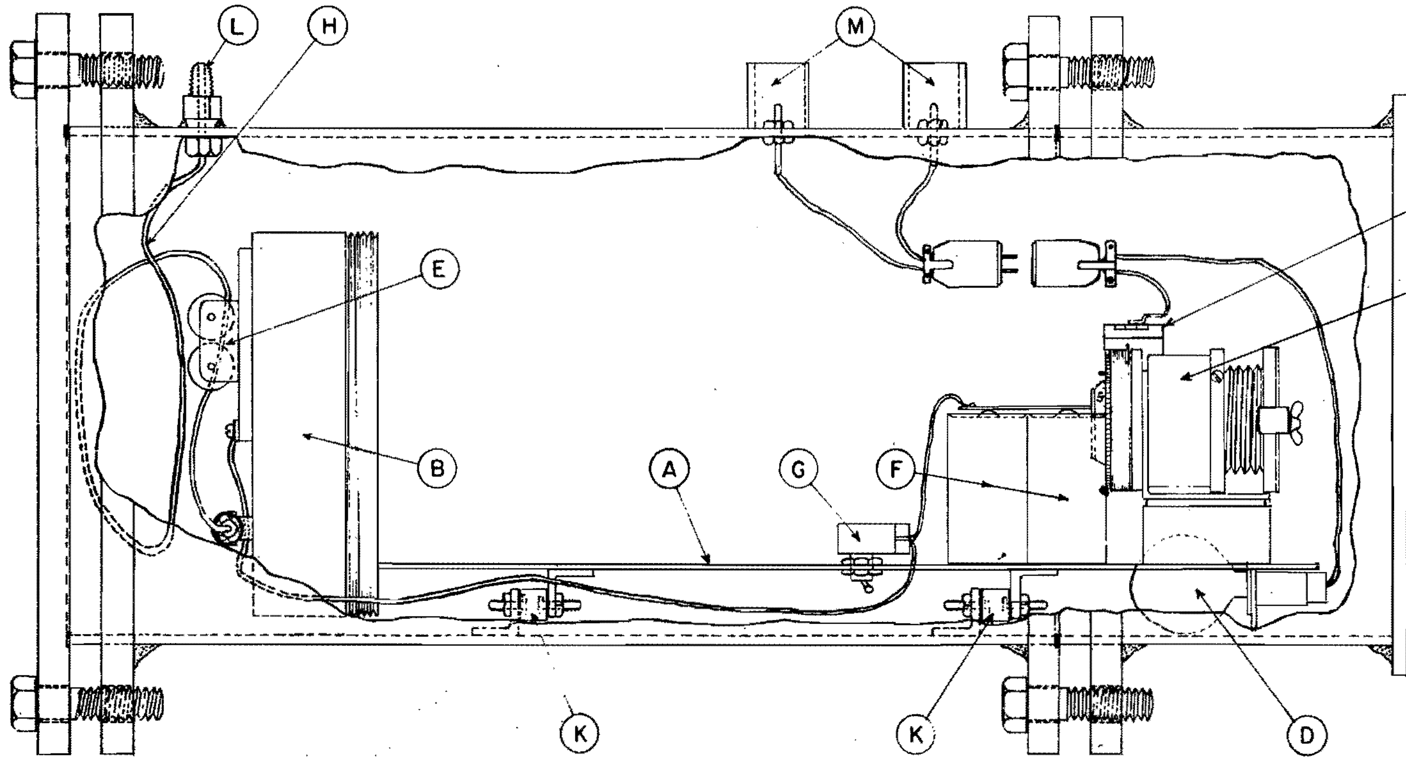


FIG. 11
BOURDON DEPTH GAUGE
UERL WOODS HOLE, MASS.

TRACED BY HRC
8—2—46

complete before the shock wave from the detonation reached the gauge (Fig. 9). When the gauge was brought up after each shot the solenoid was actuated once more in order to close the camera shutter before opening the case. The film was developed in D-72 for about one minute. A contact print from a typical record is shown full size in Fig. 12b.

The dial gauges were calibrated using a gauge tester[9/] of range 0-1000 lb. This tester is of the dead-weight free-floating piston type and requires that the calibration be made on a steady platform where the tester cylinder can be maintained vertical. As this condition could not be met at sea except under very rarely favorable conditions, it was necessary to calibrate a dial gauge ashore, and to use it as a secondary standard at sea. For the secondary calibration the gauge tester was used as a source of hydrostatic pressure by means of which the working gauge could be compared with the secondary standard. Each time a working gauge had been exposed to a detonation or other rough treatment it was recalibrated by means of the secondary standard before further use. Occasionally all gauges were recalibrated ashore with the gauge tester.

The primary calibration of a gauge could be duplicated to better than 0.5%, a secondary calibration to better than 1.0%. The gauge was frequently found to read higher after a shot than before; usually a uniform shift over the whole range was found, indicating a zero-shift of the mechanical train rather than permanent deformation of the Bourdon element.

The final pressure is estimated to be subject to a maximum error of less than 2% of the reading. In addition a slight error may be introduced due to tilting of the rig which may displace the gauge slightly above or below the charge.

5. Bubble Period Measurements

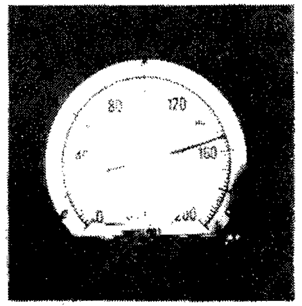
The first bubble period for each shot was recorded by piezoelectric measurement.

Three rochelle salt gauges were hung over the side of the ship on a weighted dropline. One gauge, roughly 30 ft below the surface, was a trip gauge; the other two, 10 ft above this, were the recording gauges - one a spare. The gauge cables were approximately 100 ft long and had no compensation or padding.

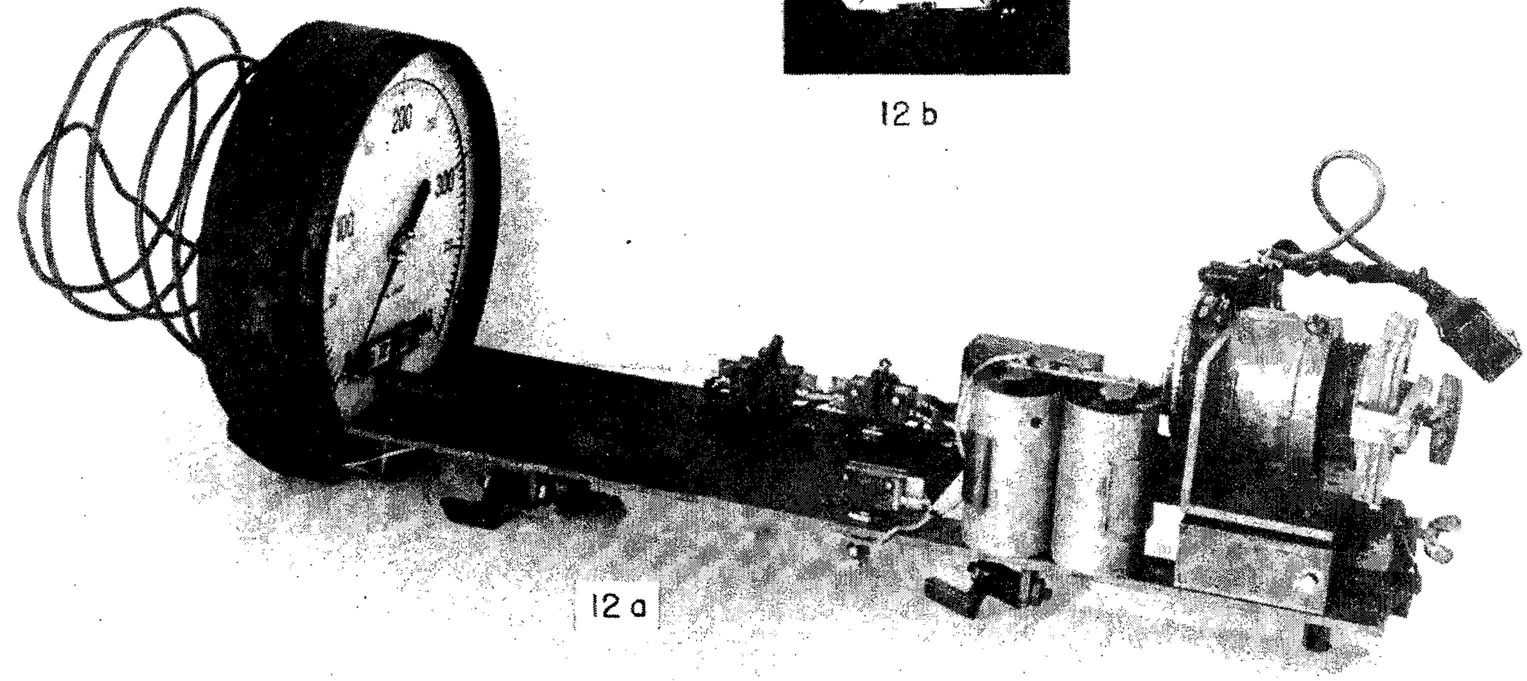
The electronic gear[10/] consisted of a power unit, a DuMont 208

9/ Ashton 0-1000 lb range gauge tester. Ashton Valve Company Cambridge, Massachusetts.

10/ Electrical Instruments for Study of Underwater Explosions and other Transient Phenomena, by R. H. Cole, David Stacey, and R. M. Brown. OSRD 6238, NDRC A-360.



12 b



12 a

Fig. 12 a. Bourdon Depth Gauge out of case.
Fig. 12 b. Typical pressure record.

oscilloscope equipped with a rotating drum camera, a preamplifier for the trip signal, a time delay beam brightener, and a multivibrator. Timing was accomplished by use of a rapidly flashing crater tube installed in the field of view of the camera and driven at a known frequency.

Bubble periods were read from the film records, the initial point being taken as the point where the base line was first interrupted by the shock wave. While the bubble pulse was sometimes irregular, the central point of the rise was always taken for the time of occurence of the bubble minimum. Measurements were made with a 0.01 in. ruler and were accurate to about 1%[11/]

Periods were also taken from the photographs of the bubbles. The bubble diameter was plotted against time and the period was found from the smoothed curve. This is not as precise as the electronic method, but usually checked it to better than 2%. The second and third bubble periods reported in a forthcoming NavOrd report were found by this method. (NavOrd 97-46.)

6. Miscellaneous Techniques

A number of useful devices and techniques not described above have been developed during the course of this work. Some of the more important of these are described in this section.

The flash bulb cases used were somewhat larger than those used previously (Ref. 1) due to the necessity for greater illumination and were designed to hold five No. 31 flash bulbs each (Fig. 13). The five sockets were wired in parallel and connected to the outside through two waterproof connectors, (Ref. 1, Fig. 142). The window on the front is of lucite which withstands pressure and shock rather well. It was used without gasketing. A 3/4 in. thick disk could be used several times 9 ft from a 1/2 lb block of explosive; however, the occasional cracking and leaking around the edges was so costly of material and time that eventually several thicknesses totalling up to 2 in. were used with entire satisfaction.

It has been found necessary to support the electrical cables every 100 ft or so by attaching them to the steel cable supporting the rig. The wire clip shown in Fig. 14 was hung on the cable and a hook which was taped to the electrical cables snapped into the end of the arm. The weight of the cables held the clip in position. To prevent fouling in the equipment, the cables were led from the rig up one of the support guys and taped to a point just below the ring.

11/ Measurement of Bubble Pulse Phenomena II. Small Charges, by A. B. Arons, A. Borden, and B. Stiller, OSRD 6578, NDRC A-470.

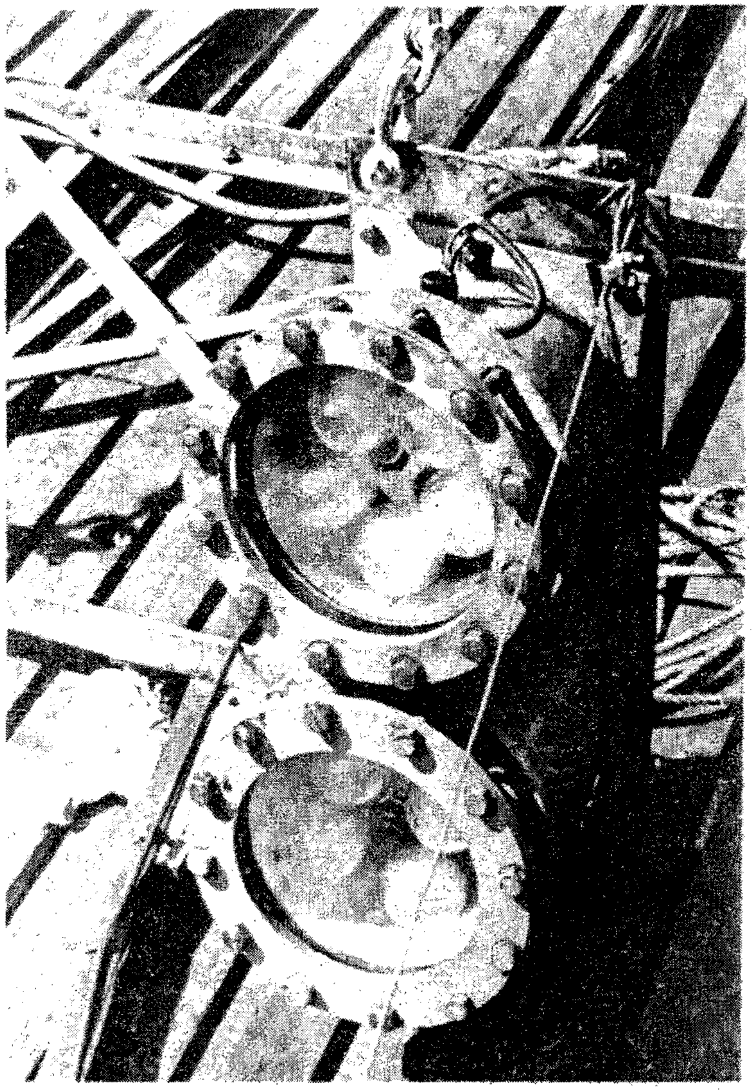


Fig. 13. Flashbulb cases mounted on rig.

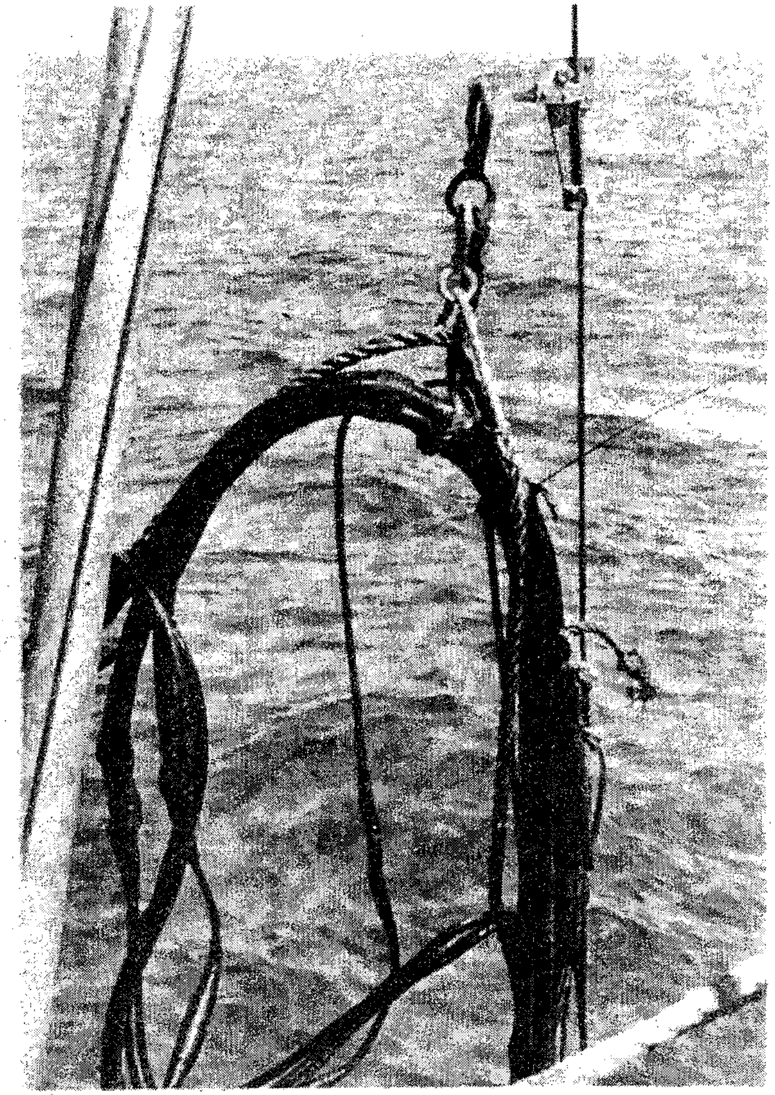


Fig. 14. Wire clip supporting electrical cables.

Connections in the cables leading to the rig were made with special waterproof splices. The technique used was to cover the entire joint for a distance of 8-12 in. on either side of the splice with three tapering layers of Bostik[12] alternated with rubber tape and a final cover of friction tape. Unless very carefully made, these joints soon leak and must be replaced, besides being slow and cumbersome to prepare. A splice which appears to be much more satisfactory can be made quickly by slipping a length of rubber tubing over the connection, smearing Bostik inside the ends of the tube and tying copper wire around them. This has not as yet been exhaustively tested.

When more than one circuit was involved, it was very important to use unique pairs of plugs for each circuit, so that it would be impossible to make the wrong connections on plugging in. A great deal of contact trouble was eliminated when ordinary AC plugs were replaced by Jones[5] plugs.

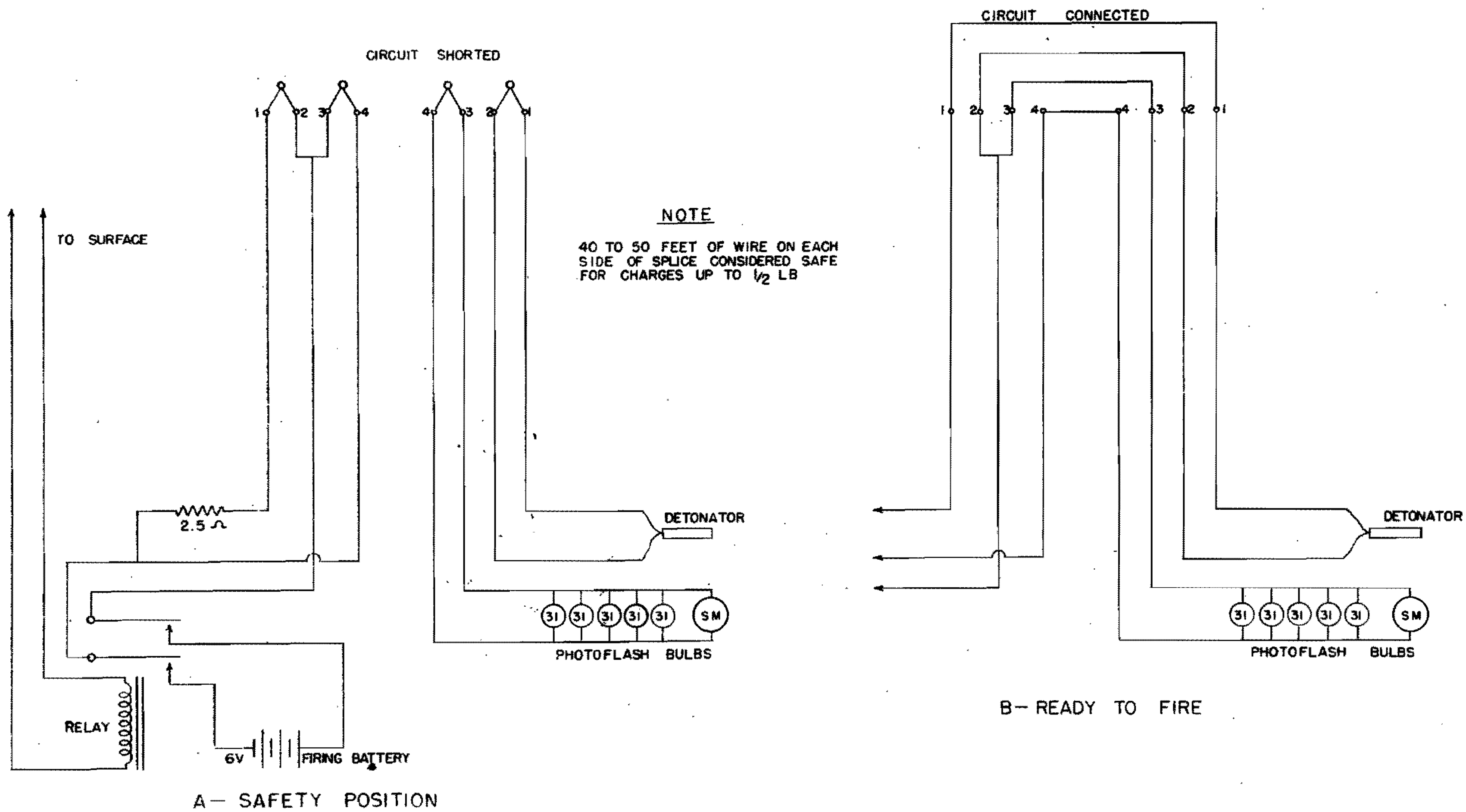
To prevent accidental firing of the charge while on deck, the firing line was always isolated and shorted. The shorting splice was under control of the man arming the charge at all times, either by a lock with the sole key in his possession, or by being where he could see it clearly at all times. With the Fastax camera, the "safety splice circuit" shown in Fig. 15 was used. This is complicated by the necessity for isolating the flash bulbs, as well as the charge, from the firing relay which might be tripped by the rig striking a solid object - such as the ship's rail. The detonator and flashbulbs are shorted as shown in A while the charge is on deck; when it is in the water and has been lowered to a safe depth, 40 to 50 ft as shown, the safety leads, which are brought up the lowering line, are connected ready for firing as shown in B.

7. Discussion

Both of the high speed cameras used were fairly satisfactory, but had some limitations. The pictures made with the Eastman camera were very sharp, but the angle of view is quite small. This limits the size of the operation being photographed, since, because of water clarity, it is not possible to move the camera away to a very great distance. The Fastax camera has a much greater angle of view than the Eastman in the longer dimension of the picture and slightly greater in the narrower dimension. The pictures made with this camera are not so sharp as those made with the Eastman, particularly near the edges of the film. Both cameras proved rugged in service and gave no mechanical trouble.

A high-speed camera which has a wide angle of view and which gives sharp pictures would be very desirable for this work.

12/Bostik Cement S292C, BB Chemical Company, Cambridge, Mass.



TRACED BY HRC
8—21—46

FIG. 15
SAFETY SPLICE CIRCUIT
UERL WOODS HOLE, MASS.

The Jerome camera takes a very wide-angle picture, but at a relatively slow speed; i.e., a maximum of 50 frames/sec. A camera with a lens of about the same focal length (1 in.) capable of taking sharp pictures on 35-mm film at 150-200 frames/sec would be extremely useful for any future work involving moderately large charges, or for detailed studies of the damage process on a larger scale than heretofore employed. It must be pointed out that with such short focal length lenses, the optical distortion introduced is very great and must be corrected for quantitative studies.

For future deep photography, a better depth gauge would be desirable. Unfortunately a compromise must be made between pressure sensitivity and resistance to shock, and this makes the instrument somewhat unsatisfactory. It would be desirable for some types of work to have the instrument send a signal back indicating its depth.

An unsolved problem is the lighting of large charges. The depths at which sunlight can be used probably do not extend as far as would be desirable in studies of the effect of large charges on very deeply submerged objects. No artificial light source has yet been found which will last for a full second and not be extinguished by the explosion. A rough estimate of the number of No. 31 flash bulbs necessary to illumine a bubble with a 20 ft radius as brightly as the 2 ft bubbles studied here, for a total time of only 75 msec, shows that about 10,000 bulbs would be needed.

The problem of finding the size of a distant large object underwater has been solved in a rather preliminary way by calculations involving object distance, image size and focal length of the camera. A fixed scale in the field of view at the same distance as the object being measured would be desirable, but a practical one has not been found for full scale work.

III. RESULTS

1. Free Bubble Pictures with Fastax Camera

Pictures of exploding half pound charges of TNT, torpex, tetryl, and pentolite were made at depths from 300-600 ft, using the Fastax camera. The charge was suspended in a frame of steel rod (Fig. 7), which had a surface small enough not to affect the bubble appreciably. The photographs obtained were used to find the rate of growth of the bubble, maximum bubble radii, first bubble periods as a check, and the second and third periods which were not found from the piezoelectric records. These quantitative results and their relationship to the energy of the system will be discussed in a future NavOrd report. (97-46.)

(a) Bubble cycle. Figure 16 shows a series of pictures taken of a ½ lb tetryl charge 30 ft from the camera, 300 ft deep, at 1800 frames/sec, using ten photoflash bulbs 9 ft from the charge, and the rig set up as shown in Fig. 7. The pictures shown have been trimmed down -- each one shown occupies about 1/3 of the total frame height (between perforations). To scale the operation, the white marker above the charge is just 2 ft long, and the charge is initially 31 in. below it. The camera was tilted slightly during this shot.

The first frame shows the undetonated charge, consisting of a cylinder of pressed tetryl approximately 3 in. long and 2 in. in diameter. Detonation occurred during exposure of the second frame, and the detonation light from the detonator (on top) and the charge is visible where they are not covered with friction tape. The bubble grows to a maximum size at about 14 msec after detonation and then collapses to a minimum at 27.4 msec. These points may be found by subtracting about 1.5 msec (the time of detonation) from the values given on the figure. The second maximum and minimum are not so clearly defined, but occur at about 38 and 48 msec, respectively, and beyond this the third maximum may be discerned. The total time shown, as indicated by the timing marks, is about 59 msec. The images on the original film are clearly discernible, although growing faint at the end, for a total time of about 75 msec. In the last usable frames the flash bulb intensity was about 1/6 of the peak intensity. Longer exposures can be made by a method similar to that indicated in Fig. 10.

Figure 17 is a picture of the bubble at its first maximum taken with the ocean as a background. The 24 in. white scale and part of the white-painted steel frame are shown. The contrast between bubble and water is so slight, that the outline of the bubble is discernible only by virtue of the presence of some white material there. Because this white material disappears as the bubble collapses, the bubble at minimum radius is virtually invisible against the water. As many as fourteen flash bulbs 9 ft in front of the bubble failed to illuminate it sufficiently to make the minimum visible.

Figure 18 shows the improvement effected by the use of a white background, in this case a cotton bed sheet about 4 ft behind the charge. Figure 19 shows the bubble at its minimum under the same conditions as in Fig. 18. Figure 20 shows the improvement in definition of the scale and framework made by painting them gray instead of white. The bubble is growing rapidly at the time of this picture, and the white material around it is quite evident.

(b) Appearance at minimum. The peculiar appearance of the bubble near the minimum is apparently caused by a cloud of particles in the surrounding water. It is probable that the bubble

Fig. 16. Explosion of 1/2 lb of tetryl at 300 ft depth.

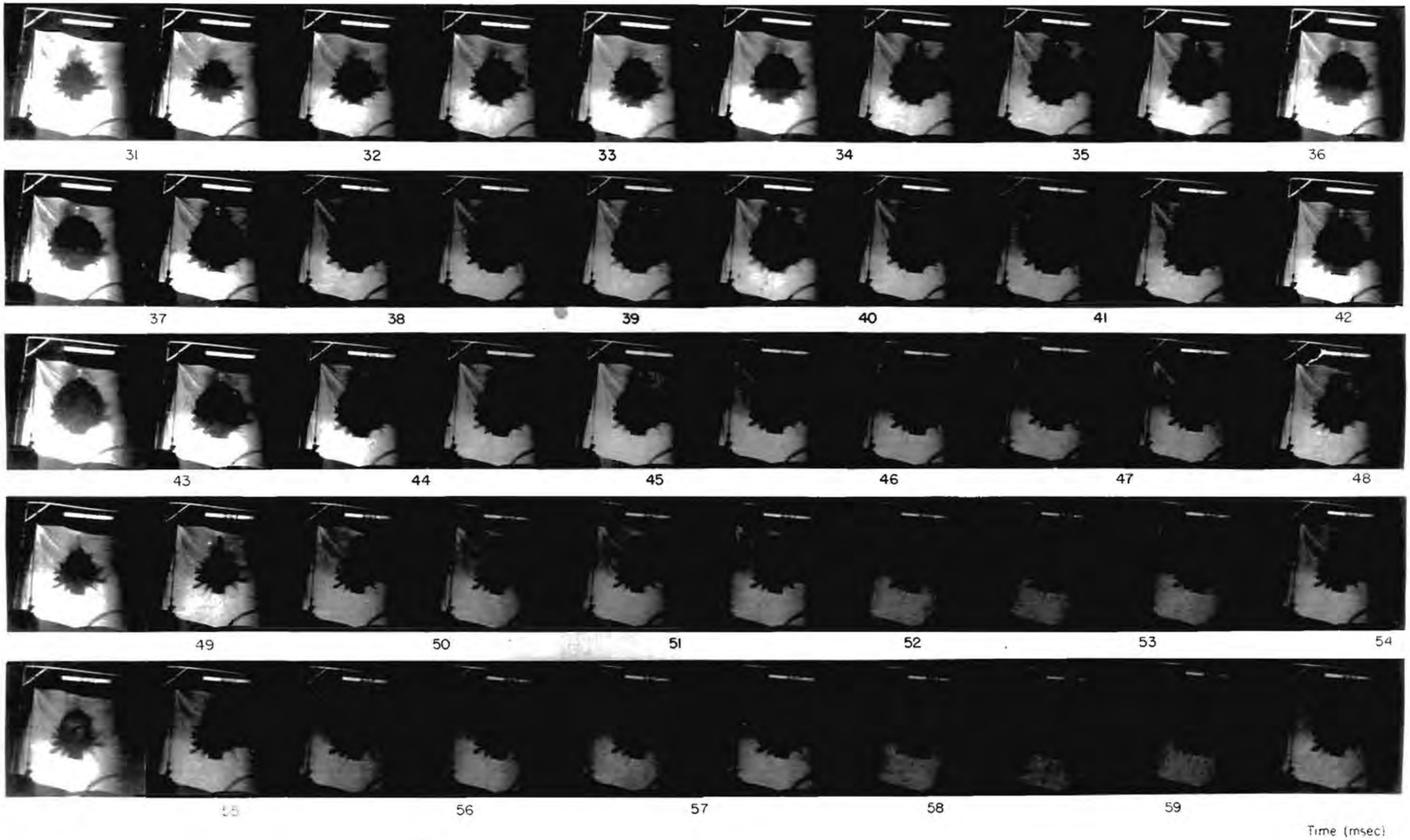


Fig. 16. (continued)

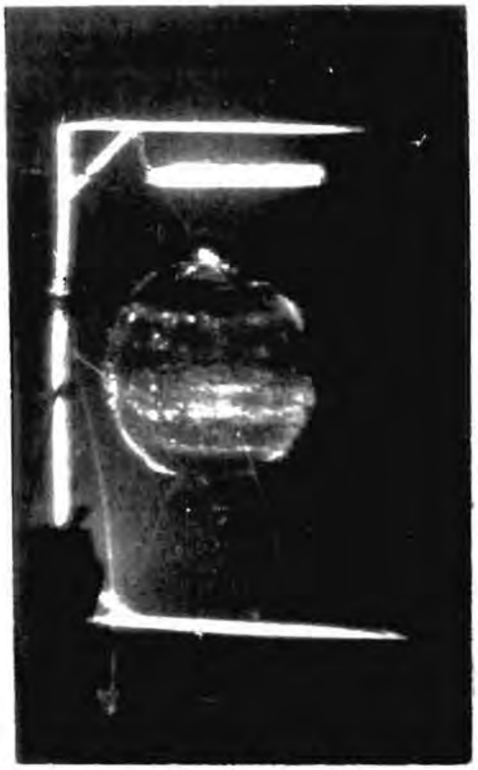


Fig. 17.

Fig. 18.

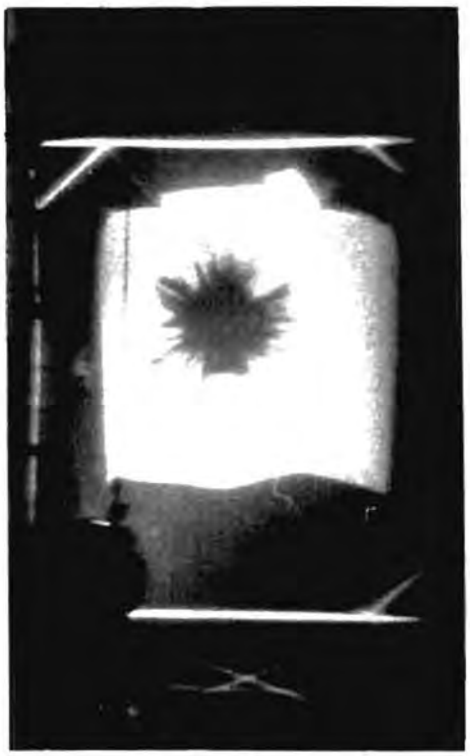


Fig. 19

Fig. 20

Figs. 17-20 Explosion product bubbles from half-pound charges.

itself retains a relatively compact form throughout the collapsing stages, but a quantity of dark colored material is left hanging in the water and masks the bubble. Photographic evidence from other laboratories13/ indicates that this material is not an integral part of the bubble, as in proximity to surfaces the bubble may be seen migrating out of the cloud of dark matter. The last few pictures in Fig. 16 show a free bubble migrating upward slightly, with a tendency to leave the streamers of dark matter behind. This happens also in the case of the upward migration of large charges as may be seen in Fig. 21. In no case do the streamers themselves ever expand laterally, as would be the case if they were filled with gases.

The dark material appeared at first to be associated with the material used to cover the charges. Many of the charges photographed were cast in cardboard containers and waterproofed with scotch tape and Tygon14/, then fastened to the rig with friction tape, often several layers thick. Horizontal bands on the bubbles appear in some cases to correspond to the friction tape around the charge before detonation as can be seen in Fig. 22. To see whether the covering material is causing the appearance of carbon streaks at the minimum, a pentolite cylinder was cast and detonated without covering, support for it being provided by two strings cast into the charge. As can be seen in Fig. 23, this did not change the appearance of the bubble near the minimum markedly, so it must be concluded that the black material comes from the explosive itself--with, of course, some additional material coming from the charge wrapping. It is probably unburned carbon and possibly tarry compounds, since the explosives studied have an oxygen deficiency. Photographs by British investigators15/ of an oxygen-balanced explcsive apparently show much less dark material at the minimum.

The carbon streaks appear less pronounced in some other photographs. Figure 24 shows a bubble at its first minimum. This picture was taken near the surface and back lighting was used. The turbulence due to migration (much greater in this case than when several hundred feet deep) is probably responsible for the different arrangement of the carbon cloud and the nearly complete disappearance of the thin streaks. If the use of back lighting is in part responsible for the minimizing of the carbon streaks, it is possible that by the use of a sufficiently bright light source the outline of the bubble itself at the minimum might be discernible through the carbon cloud. An unsuccessful attempt to do this is discussed on p. 43 of this report.

13/ Motions of a Pulsating Gas Globe Under Water, A Photographic Study, by Lt. D. C. Campbell, USNR, TMB Report 512.

14/ Tygon Corrosion-Resistant Paint, U.S. Stoneware Company, Akron, Ohio.

15/ Photographic Measurements of the Size, Shape and Movement of the Bubble Produced by 1 oz Charges of Polar Ammon Gelignite Detonated Underwater at a Depth of 3 ft. Undex 108.

It is interesting to note that the shape of the charge and the direction of detonation influence the configuration of the carbon streaks at the minimum. In Fig. 19, it can be seen that this black material assumes a broad fan-like shape at the bottom, corresponding to the flat end of the cylindrical charge which was away from the detonator. In Fig. 25 is shown the minimum appearance of a bubble from a similar charge which had been rotated through 180° so that the detonator was on the bottom. The resulting picture shows that the pattern of the carbon streaks at the minimum has also been rotated through 180°. It is thus probable that in these deep shots the pattern is not set up by the migration of the bubble near the minimum, but during the very early stages of bubble expansion.

(c) Surface roughness. The interface between the bubble and the water appears to be a region of some complexity, instead of the smooth surface found for stationary air bubbles. Examination of some of the pictures of expanding bubbles (as Figs. 1, 16, 20, 26, 27, etc.) shows this roughness to be characteristic of the bubble surface and to occur throughout the range from 1 oz to 300 lbs.

This roughness might in part be explained by the presence of solid particles in the casing of the charge, which could be projected out by the initial shock slightly ahead of the bubble surface. Figure 28 shows a few frames from a Fastax motion picture of a $\frac{1}{2}$ lb stick of pentolite, the bottom half of which was cased in a 1/8 in. thick brass tube. The metal is evidently moving out ahead of the rest of the bubble and seems to resist the inward flow on collapse of the bubble. Figure 29 shows two frames of a motion picture of a 56 lb TNT charge in which the side of the metal casing facing the camera can be seen moving out on the bubble surface for as long as 60 msec after detonation. However, since the volume of the visible excrescences on the bubbles from large charges appears to be much greater than the amount of metal present, this explanation appears insufficient.

In the case of the deeper bubble pictures, some of the material on the exterior of the bubble is often white or light colored (Fig. 20, etc.). This appearance might be due to fragments of solid material large enough to reflect the light from the photoflash bulbs. This seems reasonable, especially for the white "cap" at the top of the bubble where metallic detonator fragments should be found. However, examination of these pictures shows that this white matter changes from light to dark as the bubble contracts, and at the minimum no light colored material is visible. If we assume that the high reflectance is due to occluded bubbles, this appearance can be explained. In the region of lowered pressure behind the shock wave, small bubbles can form from gas nuclei either adsorbed on the surface of solid particles or included in them. As the explosion bubble contracts, the pressure in the surrounding water increases, thus compressing the small bubbles until they disappear. On further expansion they will reappear, but to a much slighter extent, since the negative phase of the bubble pulse is much less pronounced than that of the shock

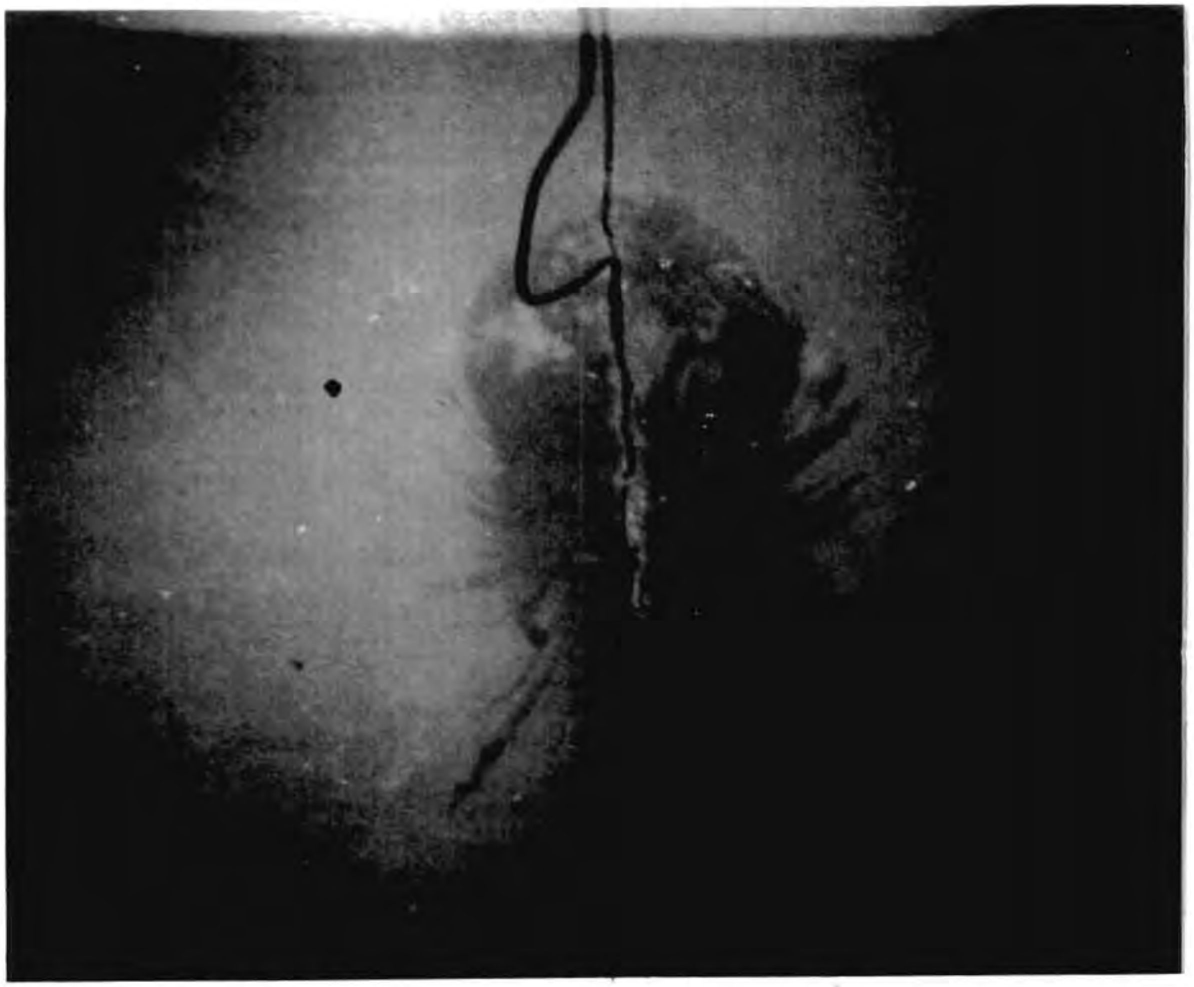


Fig. 21. Bubble from 56 lb TNT charge shortly after first minimum; approximate diameter is 8 feet.

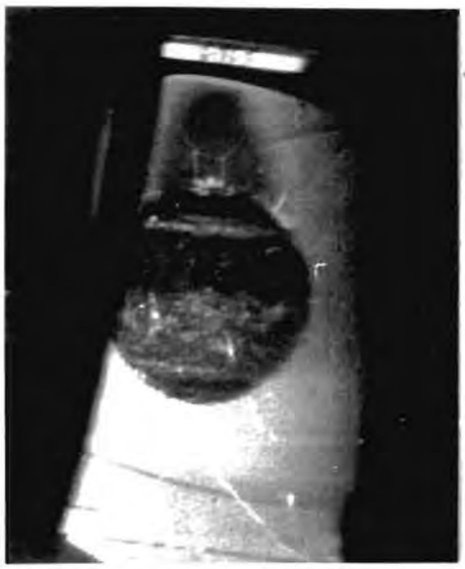


Fig. 22. Bubble from 1/2 lb charge TNT; showing horizontal bands.

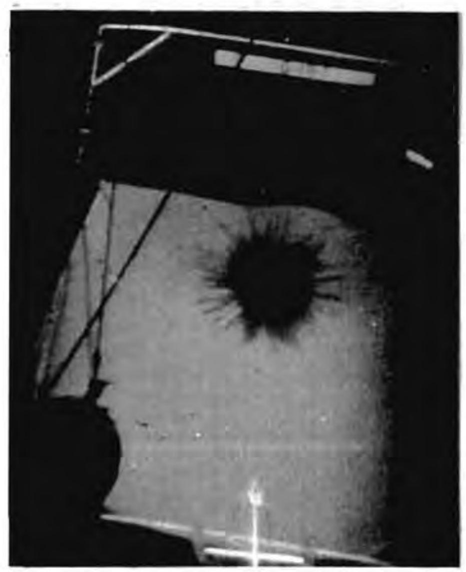


Fig. 23. Bubble from 1/2 lb bare pentolite at minimum.

Fig. 24. Bubble from 25 gm loose tetryl at minimum. Depth of 1.8 ft; back lighted.

Fig. 25. Bubble from 1/2 lb tetryl at minimum. Detonator was at bottom of charge.

Fig. 26. Bubble from 56 lb TNT 20 msec after detonation.

Fig. 27. Bubble from 300 lb TNT 80 msec after detonation.

0 1.1 2.3 3.4

4.9 11.0 19.8 23.2

Fig. 28. 250 gm pentolite stick, lower half brass cased. (Times in msec after detonation.)

10

60

Fig. 29. 56 lb charge TNT, showing side of casing on bubble surface. (Times in msec after detonation.)

wave. The reappearance of the white "cap" can be seen in Fig. 16. The presence of these bubbles associated with solid particles would explain the appearance of the surface of the large charge bubbles, (e.g., Figs. 26, 27).

(d) Effect of charge shape. That charge shape has an effect on the bubble can be seen in Fig. 30. This shows part of a set of pictures, taken at a depth of 400 ft, of a long cylindrical charge of pentolite, weight 250 gm, approximately 6 in. long by 1.5 in. in diameter. Frame 1 shows the undetonated charge. The background sheet has torn away at one corner. The time of each frame after detonation is indicated, the bubble reaching maximum size at about 11 msec. The asymmetry of the bubble can be seen best in the early stages.

Figure 31 is a graph of the bubble size as a function of time, with both the horizontal and vertical diameters of the bubble shown. It is interesting to note that asymmetry persists up to the maximum where the difference between the two diameters is about 3%. As the bubble collapses, it appears to assume a spherical shape; however, it is much more difficult to measure the bubble in this stage because of obscuration by the carbon streaks.

A more elongated charge than this should break into two or more bubbles, which would probably not reunite on collapse. The pulse[16/] emitted by the bubble from such a charge at its minimum would be a series of small shocks, instead of a single powerful pulse, since the smaller bubbles would probably not collapse simultaneously.

To examine the breaking up of the bubble from a long thin charge, a picture of a 6 ft piece of single strand primacord was taken. As may be seen in Fig. 32, a number of small bubbles were formed. The larger bubble at the top due to the detonator appears to collapse somewhat later than the others. The light lines at the edges of the bubbles are wires used to tie the charge in position.

(e) Detonation light. In a number of the pictures light from the detonation of the charge may be seen. Since the total detonation time is a matter of a few microseconds, the illumination is present for only a fraction of the time the film is being exposed and often detonation occurs between frames; however, it is of sufficient intensity to give a dense image on the film. Some examples are shown in Fig. 33. It was noticed that the charge emitted light wherever it was bare or covered only with scotch tape, but the wrappings of friction tape around the center of the charge showed up as dark bands through which the detonation light did not penetrate.

A rough estimate of the relative time during exposure at which detonation took place may be made by examination of these pictures. Figure 33a shows a dark area around the detonating charge which is doubtless the rapidly expanding bubble in its

16/ i.e., the pressure wave emitted by the bubble on collapsing to its minimum size, referred to as the "bubble pulse".

early stages. This would indicate that detonation took place fairly early during exposure of this frame and the bubble expanded slightly during the remainder of the exposure time. Figures 33b and 33c show little sign of such a bubble, so probably detonation occurred later than in Fig. 33a. Figure 33d shows a slight displacement of the light image to the right of that of the original charge. This indicates a late detonation when the image of the charge has moved relative to the film. This relative motion will take place when the square prism in the camera has turned to a rather acute angle, and the light passing through it is very greatly refracted -- enough so that the image travels faster than the film for a short time just before cut-off by the corners of the prism. This probably occurs during the last 10% of the time of exposure after an adequate exposure of the undetonated charge has been made. Since the area of the face of the prism then in the light path is relatively small, the intensity of the detonation light would be cut down appreciably, as is evident in Fig. 33d. Figure 33e shows a slightly greater displacement, and the image on the original film appears even less intense. The projections visible on the tops of the charges are the detonators.

Figure 33f shows the detonation of a torpex charge. Detonation occurs early in the picture, as is evidenced by the presence of a bubble. In this case streamers of light extend out beyond the original volume of the charge. Figure 33b, also of torpex, shows the same appearance but to a lesser extent. This phenomenon is not observed with the other explosives photographed, and fits in qualitatively, at least, with the observation previously made (Ref. 1) that aluminized explosives appear to emit more detonation light than non-aluminized ones.

2. Free Bubble Pictures with Eastman High-Speed Camera

A number of pictures were taken of the explosion of 25 gm charges of tetryl and TNT, using the Eastman Camera, at depths from 200 to 400 ft. The charge was placed about 20 ft from the camera and several feet in front of a white reflecting background of thin sheet steel. Illumination was furnished by four No. 31 flash bulbs in a case 10 ft in front of the charge. Camera speed was approximately 2200 frames/sec.

Figure 34 shows the explosion of 25 gm of tetryl at a depth of 350 ft. The scale above the charge is 12 in. long, indicating the limits of the field of view, which is about 28 x 20 in. at this distance. The bubble period is of somewhat shorter duration than in the previous pictures in this report, minimum bubble size appearing at only 11 msec after detonation because of the smaller size of the charge.

Most of the phenomena described in the section on the pictures of half pound charges are evident here; in addition a much more detailed view of the surface irregularities on the bubble is obtained. The detonator is larger in proportion to the total size of the charge, and exerts a greater influence on the shape of the bubble, distorting the top portion in the

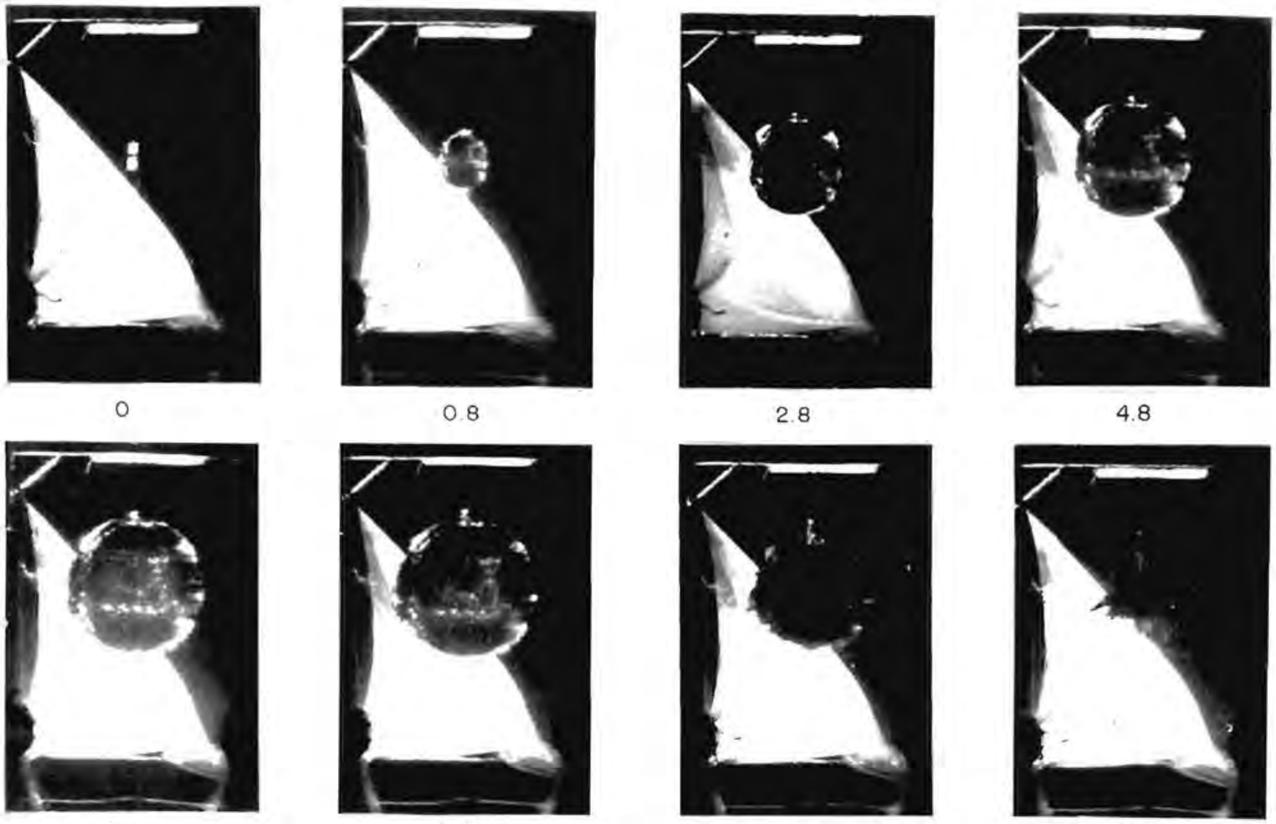
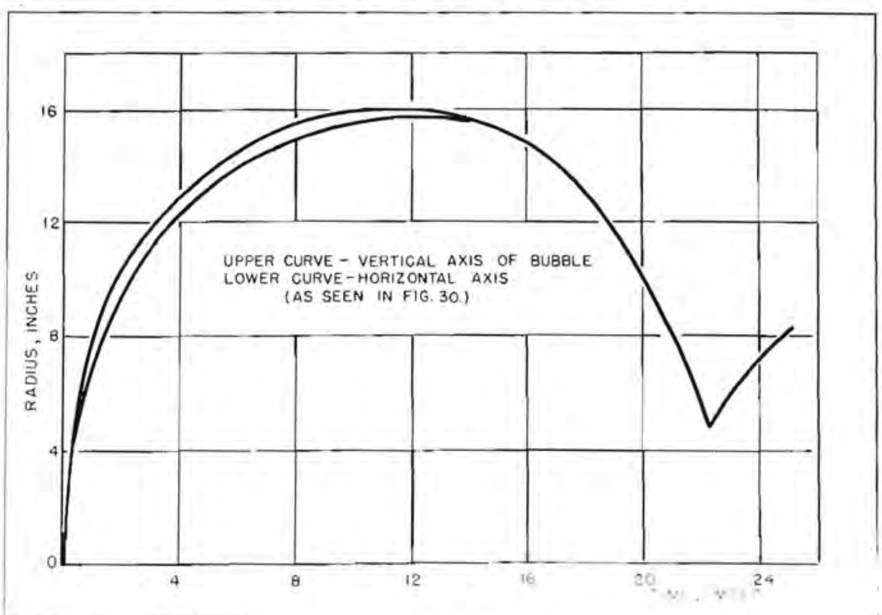


Fig. 30. Bubble from 250 gm long cylinder of pentolite at 400 ft.



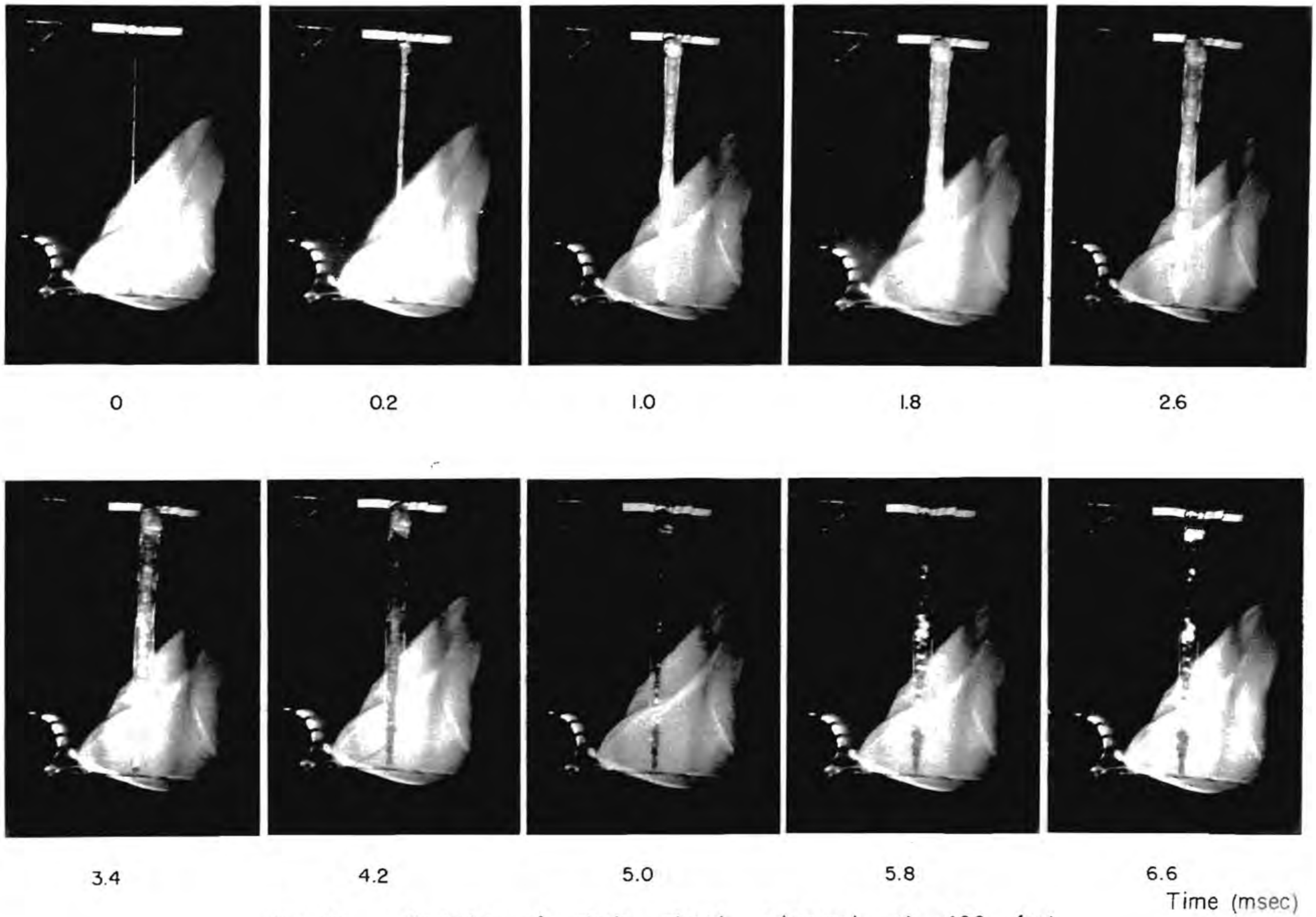
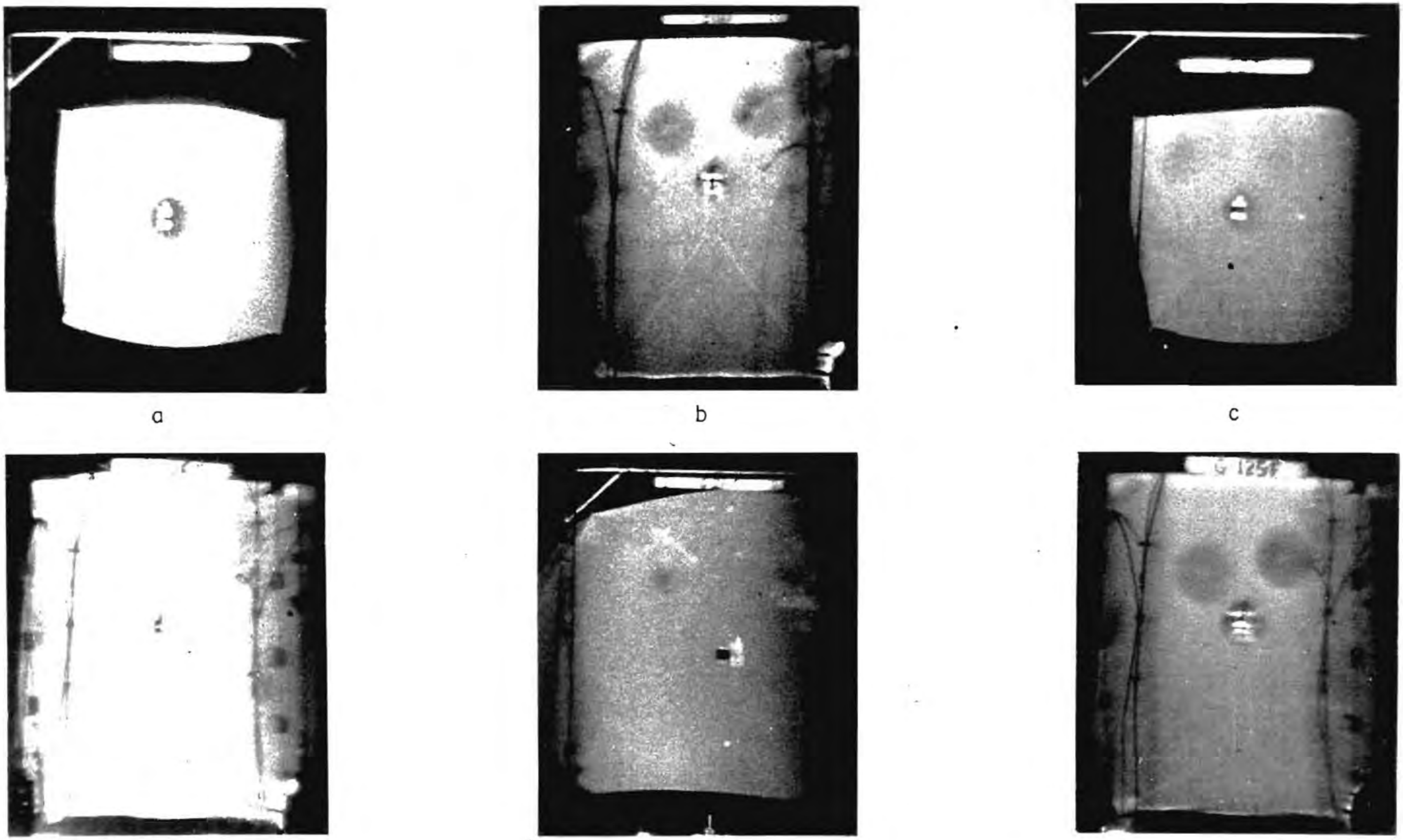


Fig. 32. Explosion of single strand primacord at 400 feet.



a b c

d e f

Fig. 33. Detonation light from half-pound charges.

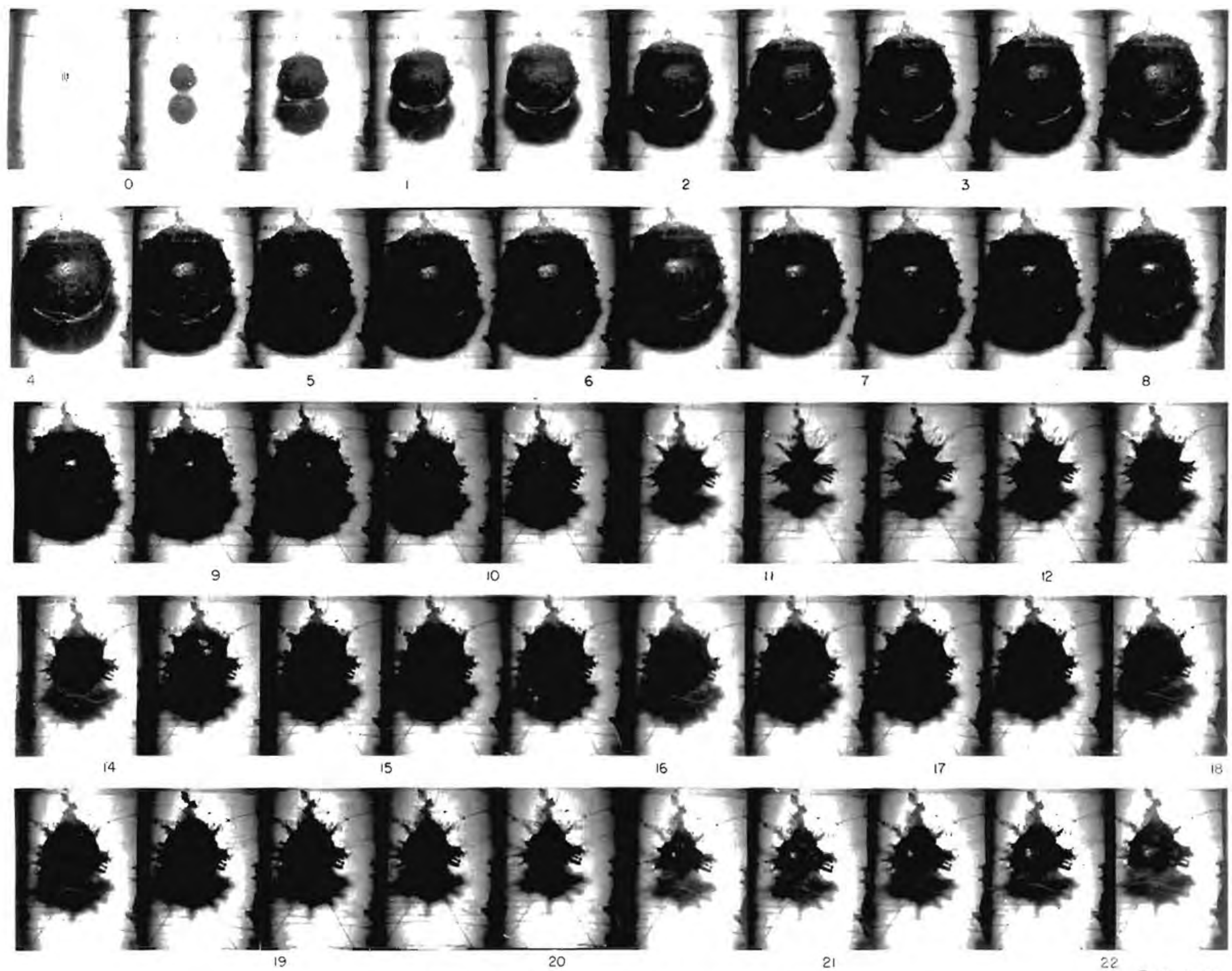


Fig. 34. Explosion of 25 gm tetryl at 350 feet

early stages and providing considerable effect near the minimum.

Some 25 gm pressed TNT charges were photographed under the same conditions. Evidence from the piezoelectric records of the bubble periods indicated that detonation was incomplete, as the periods were very short and there was little agreement among the several shots. Figure 35 shows several frames from a picture of such a charge taken at 390 ft. It will be noted that at its maximum the bubble is much smaller than that for the tetryl charge of the same weight, whereas any difference should hardly be discernible if complete detonation occurred. The latter frames of the series show clearly a piece of the charge which did not detonate.

3. Shallow Bubble Pictures

A number of underwater shots were made close to the surface of the water with both the Fastax and the Eastman cameras. The location used for the shots was a sheltered cove where there was no swell and small waves were at a minimum. The work was done from a Quonset barge equipped with a five-ton crane, using the same type of camera rig as described previously. In all the pictures back lighting was used, with two sets of No. 31 photoflash bulbs set off in sequence in back of a translucent screen behind the charge. The quality of the resulting pictures depends mainly on the clarity of the water; on days when muddy water drifted into the cove, details in the pictures were hardly discernible.

(a) Bubble cycle. Figure 36 shows selected frames from the bubble cycle for a 25 gm pressed tetryl pellet 5 ft below the surface. The dark line through the center of each frame is a cable on the rig. The flash bulbs did not come on full until about 3 msecs after detonation, so the undetonated charge is barely discernible, and a circle has been drawn around it to indicate its initial position. On the day on which these pictures were taken, the water was not particularly clear, therefore the details of the bubble are not very distinct. At this depth the maximum diameter of the bubble is about 3 ft and the camera was only 15 ft from the charge, so the edges of the bubble do not appear in the narrow dimension of the Fastax picture. Only one bubble cycle is shown because the second set of photoflash bulbs failed to fire.

The growth and collapse of the bubble appears to be quite similar to the effect at depths of several hundred feet, with several minor differences. First, as predicted by theory, the bubble period is much longer than is the case at the greater depths (compare Fig. 34). Second, small bubbles appear in the field at about 3.5 msec; this seems to be characteristic of this part of the bubble cycle whenever a charge is within 2-3 bubble diameters of the surface. This will be discussed more fully later. Another item of difference is the very apparent upward migration taking place around the minimum - much more pronounced here although of course also taking place at the greater depths.

Figure 37 shows a 25 gm charge of loose tetryl within 3 ft of the surface. The water was somewhat clearer when this picture was taken, and more details are apparent. In the first frame the charge may be seen suspended at the center of the picture. At the left edge is a chain supporting the rig and part of the half-inch steel rod which was used to make a framework in the plane of which the charge was suspended. The framework extends up and over the charge where it does not quite cut the surface of the water, visible at the top of the picture. Below the charge is a 12 in. transparent ruler which has been blackened for an inch on each end so that the distance between the marks is just 10 in. In the left hand lower corner may be seen one of the piezoelectric gauges used to measure the pressure waves emitted by the charge.

Detonation light is apparent in the second frame, and in the following two frames there is some blotting out of detail in the top of the picture, probably due to formation of small bubbles just below the surface of the water. At 3.7 sec there are small bubbles close to the camera and out of focus.

As the bubble begins to collapse, the inrushing water pulls down the surface. This process can be seen at its inception near 49.6 msecs, and the development of a considerable depression in the water surface is evident at the minimum. This recedes as the bubble grows again. The peculiar shape of the bubble at the minimum is due to the presence of the free surface so close above it. As the bubble collapses, it drags in water from all directions, the most rapid flow coming from the direction of the free surface. This causes an unsymmetrical collapse resulting in the flattening of the top of the bubble. It is probable that the bubble is actually bowl-shaped at the minimum, but the camera takes an outline picture, rather than a cross-sectional view, so this is not apparent.

Figure 38 shows the bubble cycle for a 25 gm loose tetryl charge at 2 ft below the surface. The water was quite clear for this shot and details may be readily made out. More of the water surface is visible, and the shadows cast by ripples may be seen on the background screen until after detonation. As in Fig. 37, the blotting out of the top of the picture occurs shortly after detonation and progresses to a maximum effect at 3.5 msec where the outlines of the individual bubbles are scarcely distinguishable because of their proximity to the camera. The bubble does not quite intersect the surface at its maximum size, near 33 msec.

The effect of the collapsing bubble on the surface may be seen from 46.5 msec on. In this case the surface is dragged down somewhat more violently than when the charge was at 3 ft

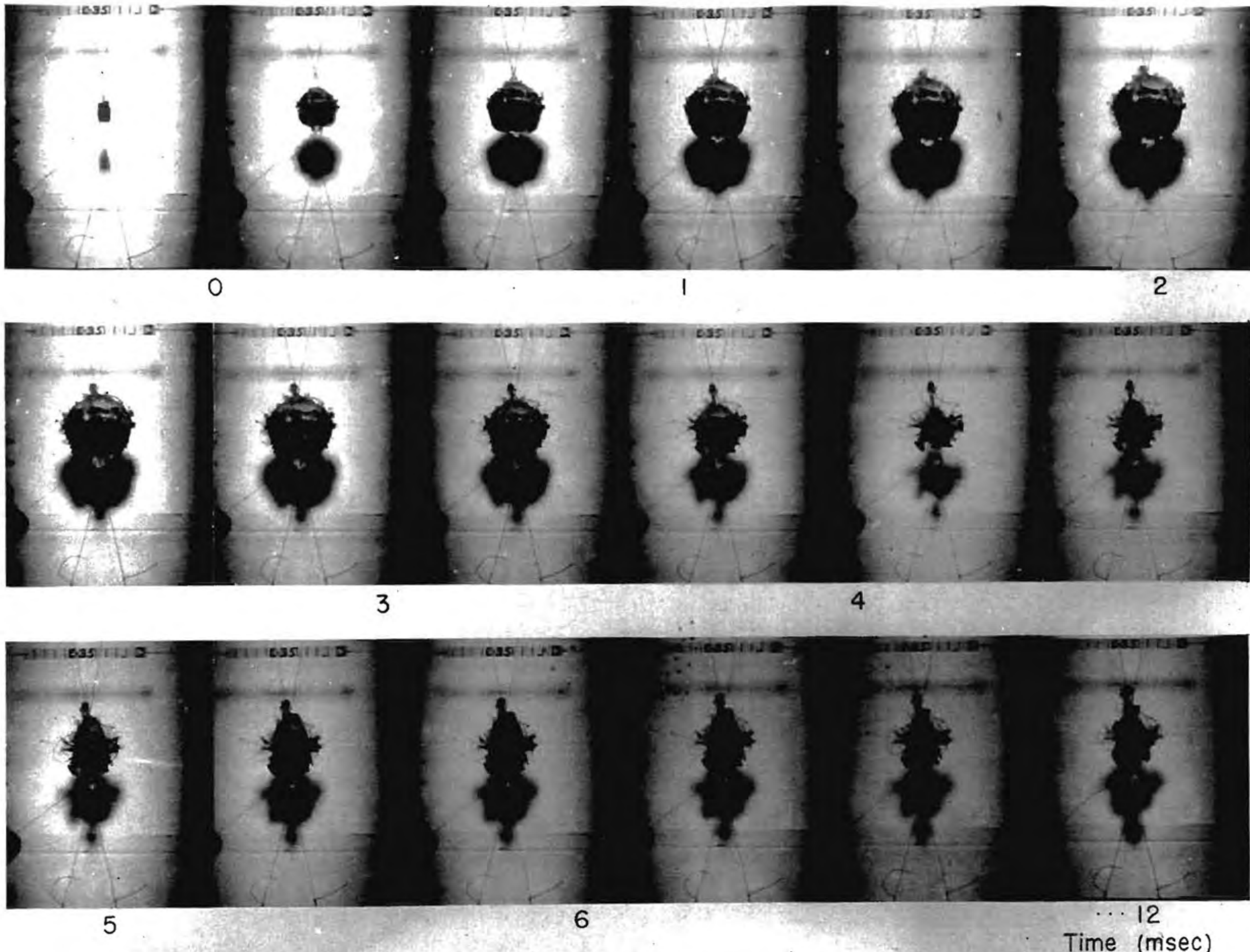


Fig. 35. Explosion of 25 gm pressed TNT showing incomplete detonation.

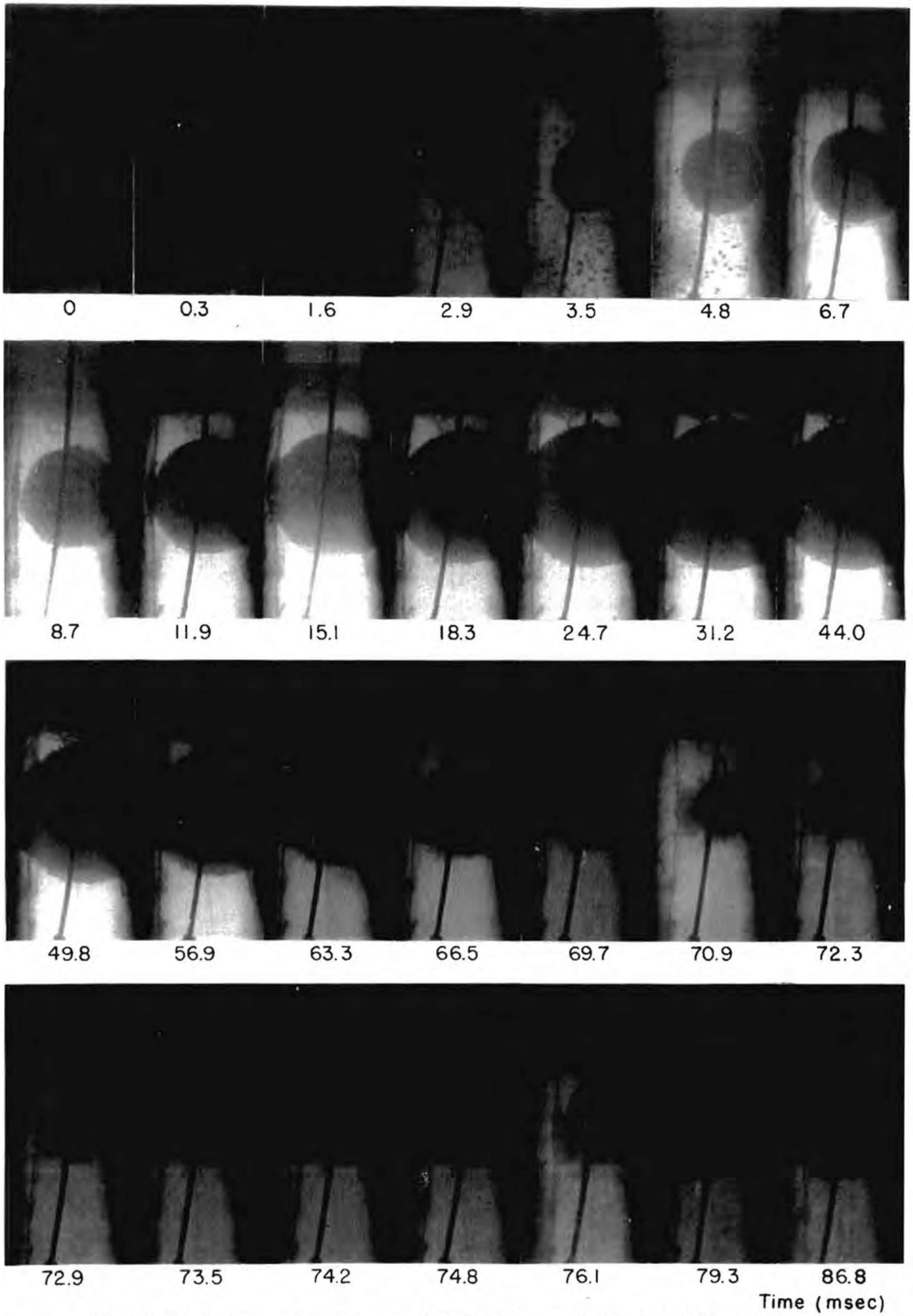


Fig. 36. Explosion of 25 gm tetryl charge 5 ft beneath surface.

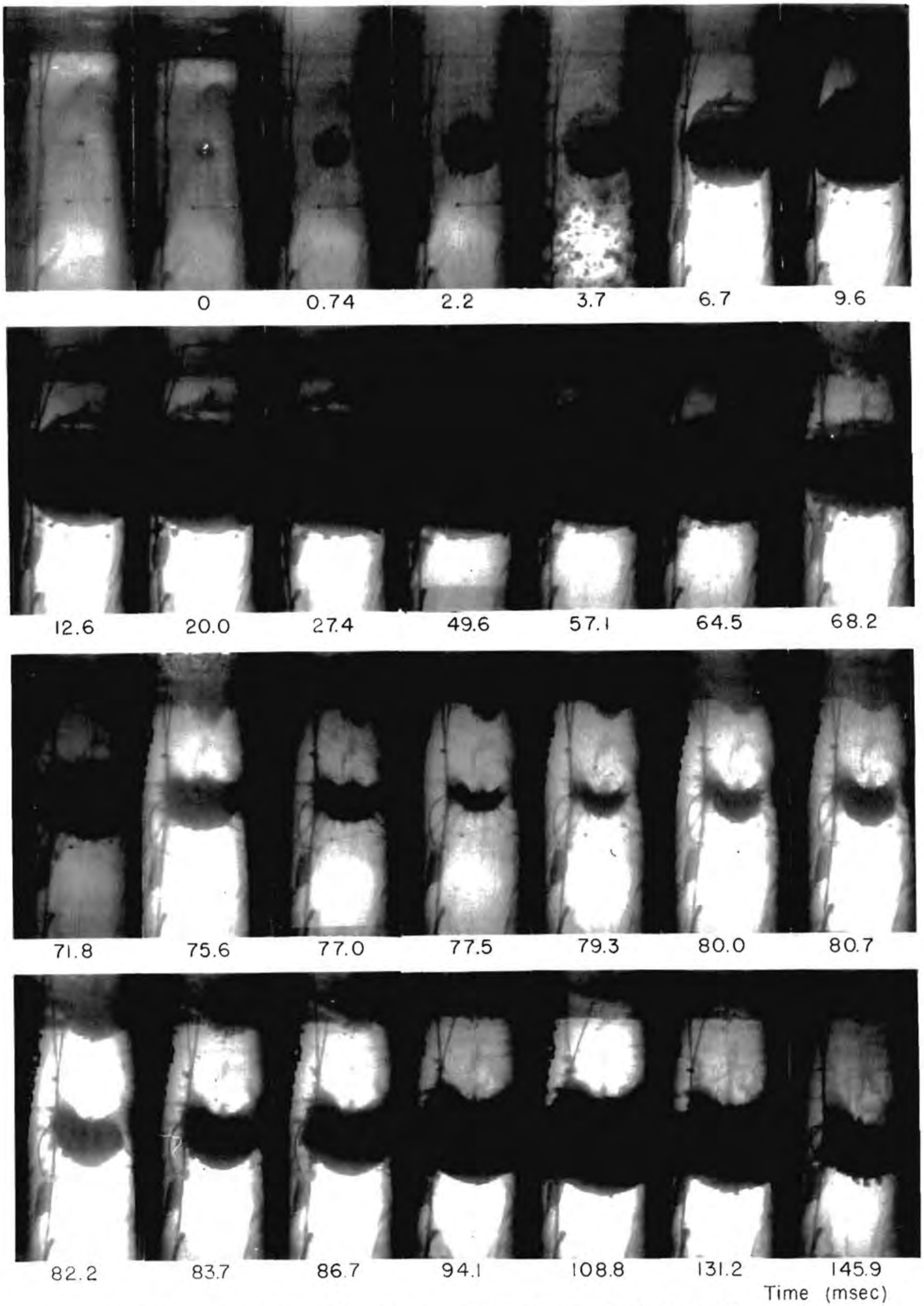


Fig. 37. Explosion of 25 gm tetryl charge 3 ft beneath surface.

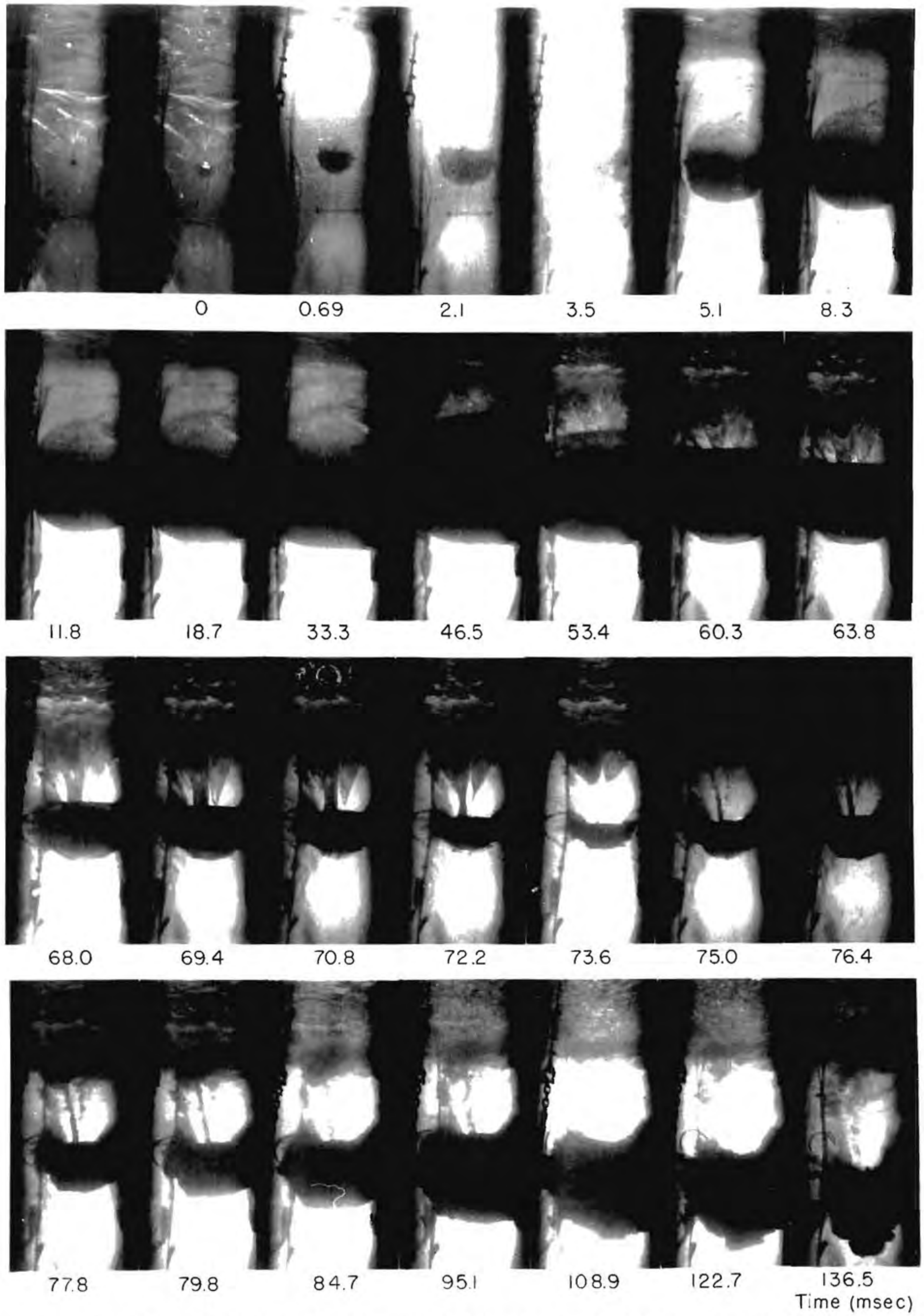


Fig. 38. Explosion of 25 gm tetryl charge 2 ft beneath surface.

and apparently forms a tubular connection with the bubble just before the minimum. It is interesting to note that this tube is collapsed at the minimum, probably because of the increased pressure in the bubble and the surrounding water, corresponding to the emission of the bubble pulse. Directly after the minimum there is some blotting out of detail in the top of the picture, and small bubbles are evident at 76.4 msec. The migration of the bubble down is evident on comparing pictures before and after the minimum.

Figure 39 shows the bubble cycle for a 25 gm loose tetryl charge 1.75 ft beneath the surface. As in the 2 ft case, small bubbles near the top of the picture obscure the view shortly after detonation and at 3.4 msec maximum obscuration occurs. At its largest calculated size, the bubble should just fail to intersect the surface. This appears to be the case in these pictures.

The interaction between the collapsing bubble and the surface is much more pronounced here. As the bubble collapses from maximum size it drags down the surface making a large tubular connection to the atmosphere above it. Enough air comes into the bubble so that its volume at minimum size is larger than for the deeper shots, and the minimum point is not very pronounced. No small bubbles in the water are detectable after the minimum. The tubular space between the bubble and the surface is not a continuous open tube after the minimum, since the bubble once more expands, rather than venting as would be expected if this were the case.

(b) Effects at minimum. In these shallow shots the greatest effects immediately noticeable occur near the minimum of the bubble. While these have been discussed in the previous section, several pictures somewhat more enlarged for detail are shown here.

Figure 40 shows the appearance of the bubbles at their minima. The bubble at 5 ft appears almost the same as those at great depths; the flow pattern has been apparently little affected by the surface. (Compare Fig. 23.) In Fig. 40b the carbon streaks may be seen also, although somewhat diminished, and in a pattern whose regularity has been disturbed by the influence of the surface. At 2 ft and shallower the carbon streaks have almost entirely disappeared, and the connecting tubes to the surface and surface irregularities may be plainly discerned.

Figure 41 shows frames before, during and after minima. Migration of the bubble may be seen on comparing the distances of the bubbles to the reference line drawn on the pictures. The times of the three sets of pictures are not comparable. Below about $3\frac{1}{2}$ ft, theory predicts that the migration will be in an upwards direction, while above this point, the bubbles should migrate down. In agreement with this, it is seen that the bubble from the charge which was initially at 5 ft migrates up slightly, while at the 2 and 3 ft depths, it migrates down. Quantitative measurements on these pictures will be given in a later report. (NavOrd 97-46.)

(c) Back lighting by sunlight. The pictures shown earlier in this report which were taken at depths of several hundred feet were front lighted, the pictures of large charge bubbles were illuminated from above, and the bubbles taken close to the surface were back lighted. Each method of lighting has its advantages as is obvious from an examination of the various pictures.

Because of the difficulties encountered in illuminating large charge bubbles, an attempt to photograph a charge from beneath was made, using sunlight from the surface as the light source. It was hoped that this lighting scheme might show the outline of the bubble at the maximum and make visible some trace of the bubble inside the carbon streaks at the minimum, with the eventual objective of trying this technique with full scale weapons.

The pictures resulting from the explosion of a $\frac{1}{2}$ lb charge of torpex under these conditions are shown in Fig. 42. The first frame shows the charge before detonation (inside circle) and the general appearance of the surface from beneath before the effects of the explosion diffuse the light. The sun is apparently to the right of the picture and just outside the field of view. As the bubble grows, its outline is clearly discernible, even near maximum size when only one edge is in the field of view. The one foot celluloid scale is clearly seen in the fifth frame just below the bubble.

The minimum occurs at about 200 msec, but the picture is unfortunately too blotchy to permit judgment of the exact time. Some carbon streaks can be seen, but small circular blots in the picture cover up details. It is not possible to discern the bubble inside the carbon streaks even on the original negative. As the bubble migrates upward, the outline of the carbon cloud becomes very irregular, as seen in the last frame.

This method of lighting offers some promise and should be studied further. In particular, it would be worth while to try shots with the sun directly above the camera, and to go to much greater depths.

(d) Cavitation. In most of these shallow shots, small bubbles persisting for a few milliseconds appear shortly after detonation. In a few cases these appear also after the bubble minimum. Examples of this behavior are found in Figs. 36-39.

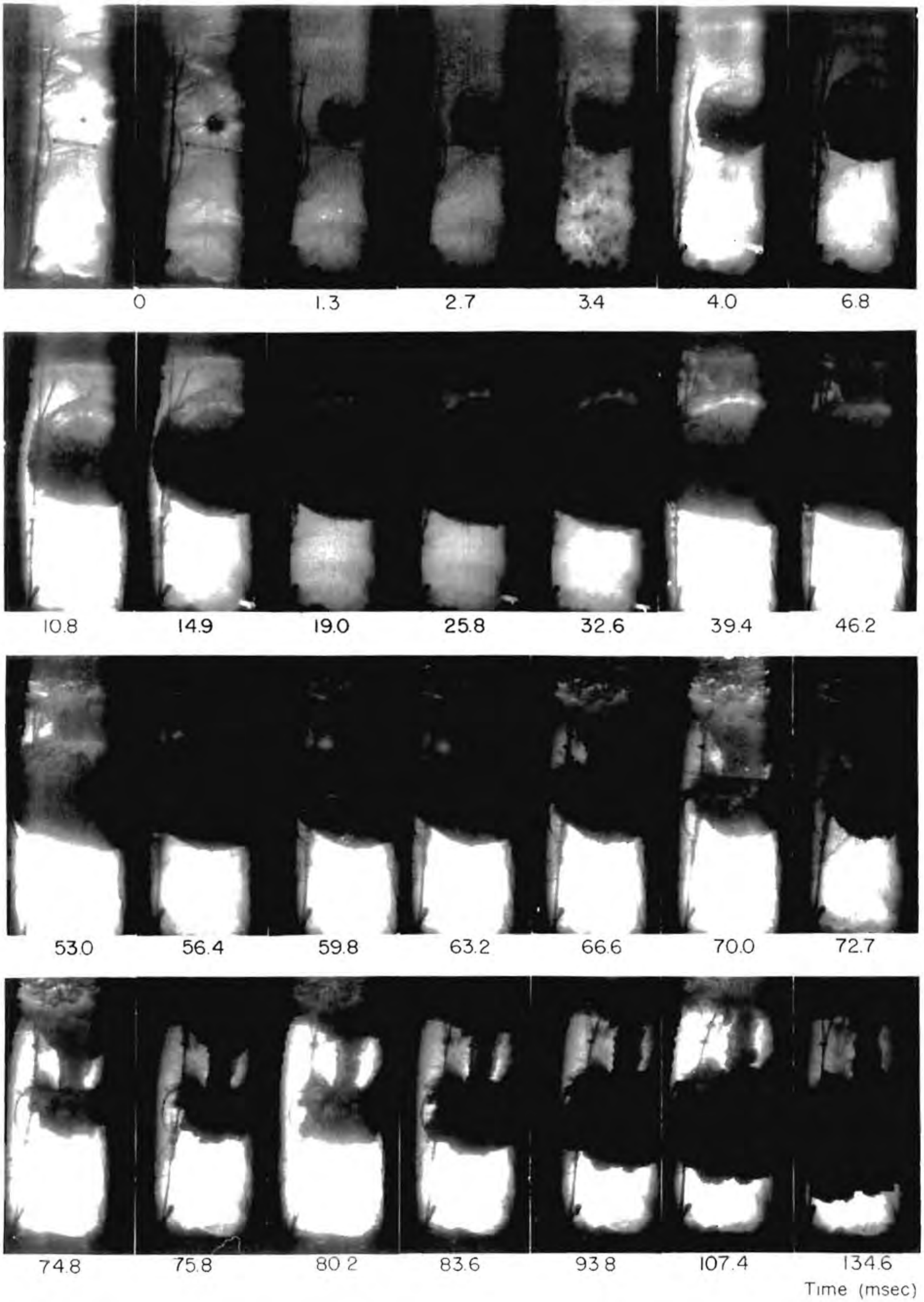
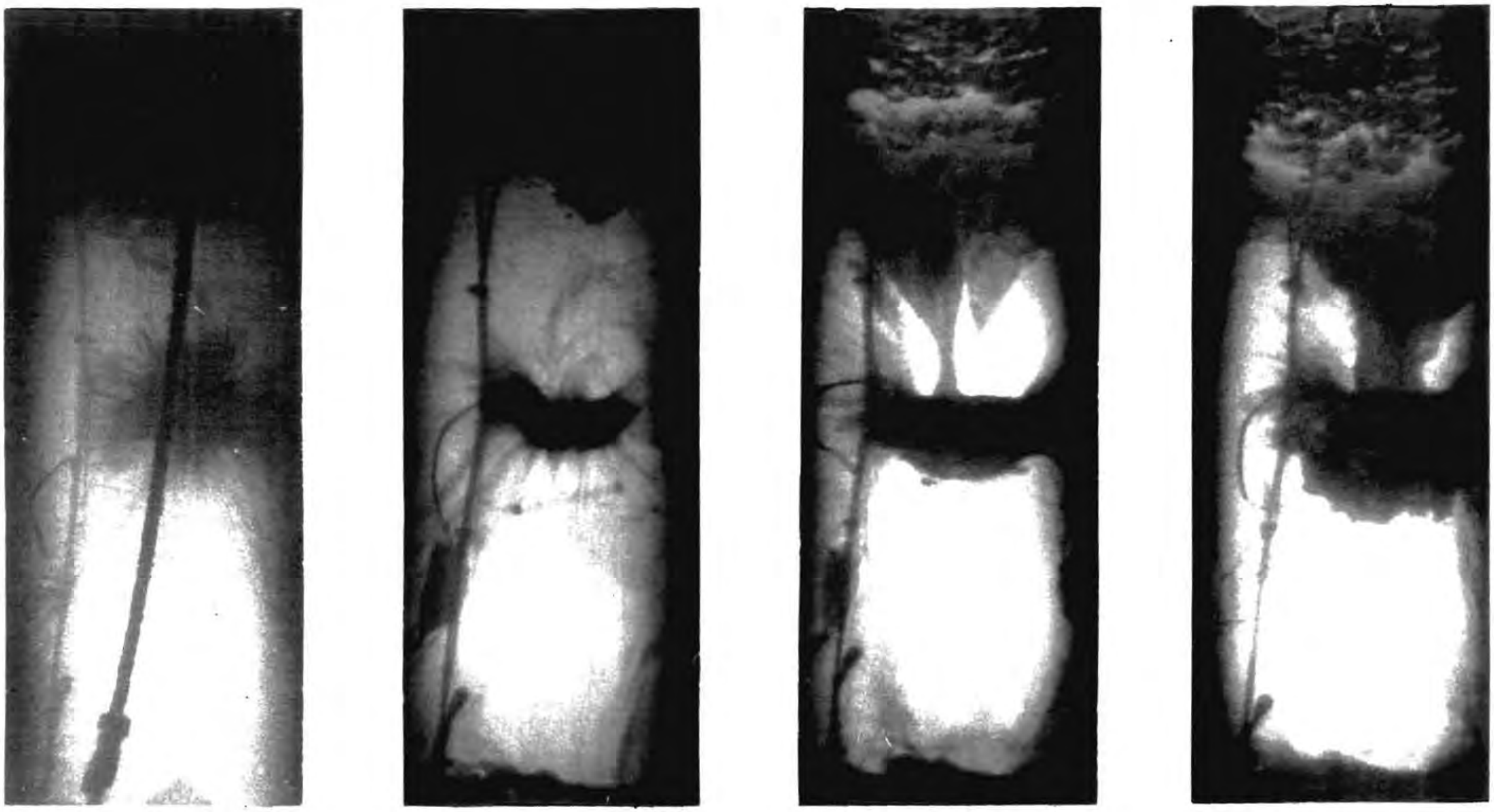
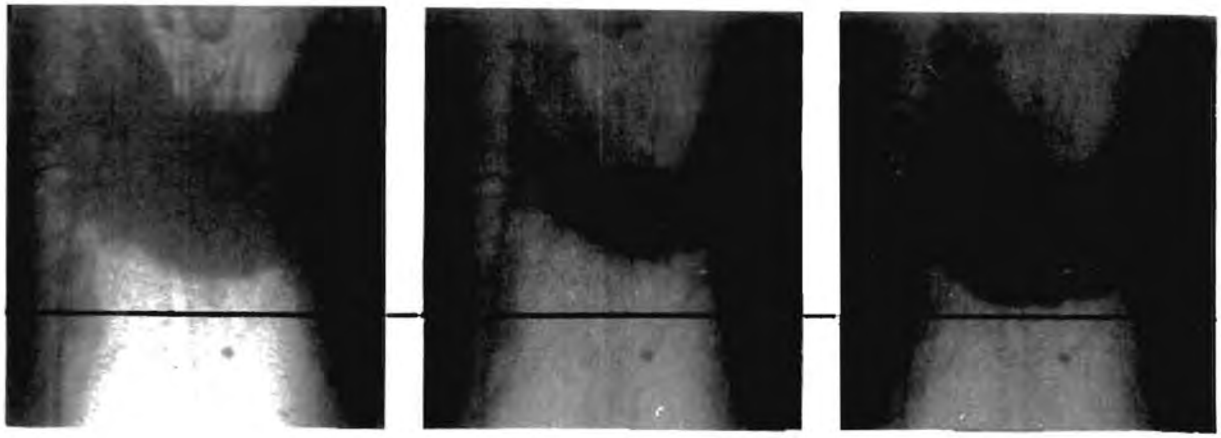


Fig. 39 Explosion of 25 gm tetryl charge 1 ft 9 in beneath surface

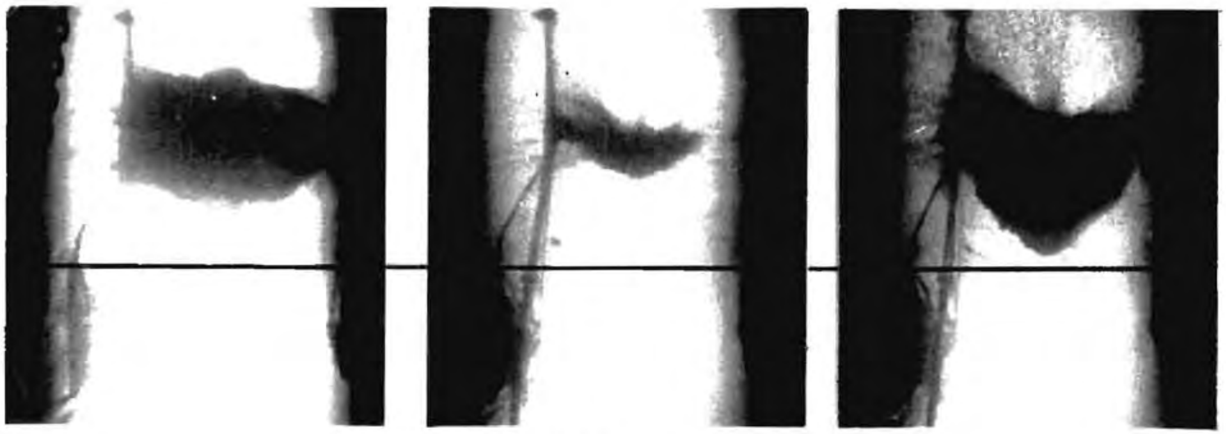


(a) depth 5 ft (b) depth 3 ft (c) depth 2 ft (d) depth 1 ft 9 in.

Fig. 40. Appearance of minima of bubbles from 25 gm tetryl charges near surface.



DEPTH 2 FT



DEPTH 3 FT

DEPTH 5 FT

FIG. 41. MIGRATION OF BUBBLES FROM 25 GM CHARGES NEAR MINIMUM.

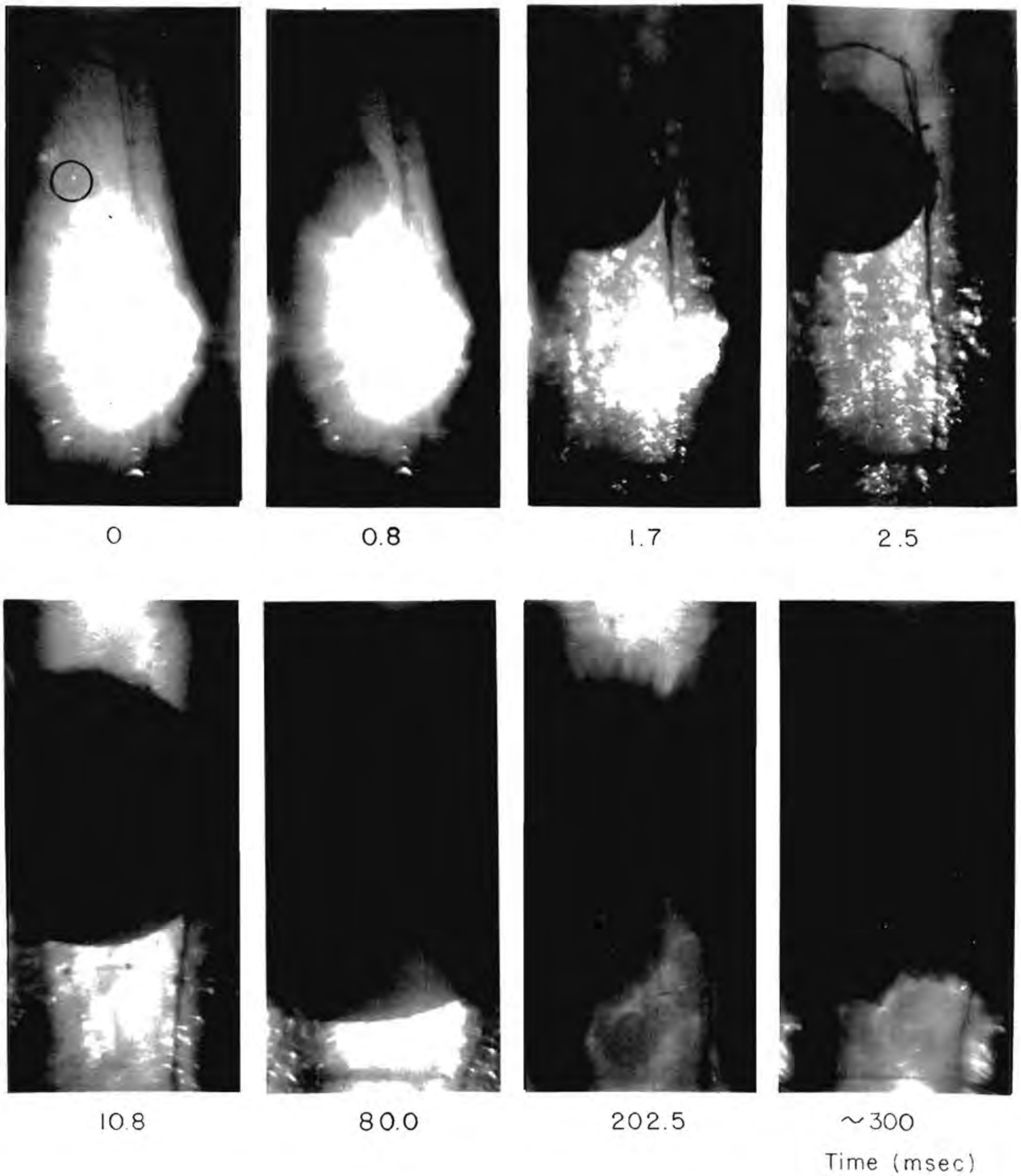


Fig. 42 Explosion of 1/2 lb torpex charge 4.5 ft beneath surface and vertically above camera. Sunlight illumination.

water near the surface of the ocean is ordinarily saturated with dissolved air; it also contains microscopic living organisms and small suspended particles. Even in the clearest ocean water it is estimated that there are several thousand small organisms per liter near the surface[17]. Thus conditions would be favorable for bubbles in the water whenever the pressure becomes sufficiently negative. This may happen under the circumstances studied here whenever a shock wave is reflected from a free surface, when a shock wave encounters an air-backed plate[18], or in the region of negative pressure behind a shock wave..

Figure 43 shows several frames from a picture of a 25 gm loose tetryl charge exploding 15 in. below the surface. In this series it appears that small bubbles approach the camera rapidly from a region in the upper part of the picture and at 3.8 msec have come so close to the window in front of the camera lens that the picture is almost completely obscured. The camera is 15.5 ft away and at the same depth as the charge so that the arrival time of the shock wave is 3.1 msec and of the negative wave reflected from the water surface 3.2 msec. The small bubbles apparent at first near the surface are probably caused by a region of negative pressure just under the surface of the water; the time of appearance and location of these corresponds to the position of the reflected shock wave. The appearance of large blurry bubbles later may be due to the proximity of these bubbles to the camera lens or possibly to the formation of a new set of bubbles from the interaction of the shock wave with the front of the camera case which might act as an air-backed diaphragm. A very similar sequence, at 2 ft, but one which does not include every frame, is shown in Fig. 38.

What seems to be a different result is shown in Fig. 44 where in both series of pictures the 25 gm tetryl charge was 5 ft below the surface. Figure 44a was taken with the Eastman camera, approximately 11.5 ft away from the charge and at the same depth. The arrival time of the primary shock wave at the camera is 2.3 msec and of the reflected shock wave 3 msec after detonation. Since the bubbles first appear at 2.6 msec and seem to be close to the camera, they apparently are a result of the primary shock wave interacting with the camera case. It is probable that the reflected shock is of much less importance here because of its considerably slighter intensity; in any case any contribution it makes is not evident.

Figure 44b was taken with the Fastax camera at a distance of 15.5 ft from the charge. No bubbles are visible until 3.6 msec. The arrival time of the primary shock wave is 3.1 msec

17/ The Oceans, by Sverdrup, Johnson and Fleming, Prentice-Hall, New York, 1942.

18/ See studies on cavitation in Ref. 1.

while the reflected shock arrives at 3.9 msec. The rather sudden disappearance of the bubbles between 5.1 and 5.8 msec precludes the hypothesis that they are due to the negative phase of the shock wave, since this is believed to last considerably beyond the bubble maximum.

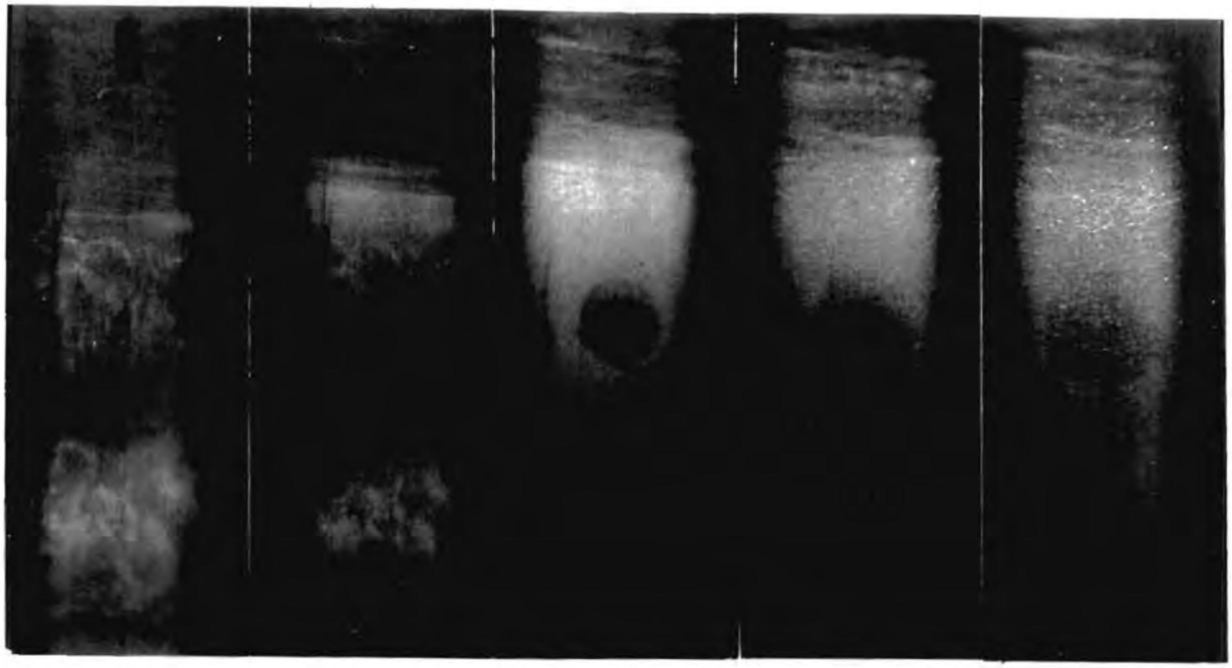
Interestingly enough, another set of bubbles appears in Fig. 44b after the disappearance of the large bubbles. These are first distinguishable at 7.1 msec as small black specks above the bubble which increase in quantity and finally disappear by 10 msec. The time of appearance does not seem to be associated with any simply reflected shock wave, except possibly from the ocean bottom.

In the cases where caviation appears after the bubble minimum, the effects are usually less pronounced. Examination of the sixth frame shown in Fig. 41 will show such a set of bubbles. A more complete series appears in Fig. 37 and Fig. 38, but are not very distinct in the reproductions. The times of appearance after the emission of the bubble pulse (assumed to occur when the bubble appears smallest) correspond roughly to the time intervals mentioned above for the surface reflected shock wave.

The same effects occur but are more pronounced when larger charges are used. Figure 45 shows a few frames from a series taken of a $\frac{1}{2}$ lb torpex charge at a depth of 4.5 ft. No effect is evident until 3.3 msec after detonation. The primary shock should arrive at the camera at 3.1 msec and the shock reflected from the surface at 4 msec, so this is evidently similar to the case shown in Fig. 44. The persistence of the bubbles is considerably greater than for the smaller charges; individual large bubbles very close to the window may be distinguished as vague blurs lasting 5-6 msec. It seems likely that large bubbles, once formed, can resist collapse for a greater length of time than small ones. Photographs taken of 56 and 300 lb charges (to be reported later) indicate that this may well be the case.

(e) Surface pictures. In a number of these shallow shots, motion pictures of the surface of the water were also taken in air, using a (16-mm) Ciné Kodak Special camera. The camera was about 25 ft away and 6-8 ft above the surface of the water. Its position relative to the charge was not measured exactly, and there are no scales in the pictures; however, qualitative observations may be made.

Figures 46 to 48 show simultaneous surface and underwater pictures of explosions of 25 gm loose tetryl charges close to the surface. Each surface frame is matched with the underwater frame which was exposed as nearly at the same time as could be determined. The underwater camera was run at about 1500 frames/sec and the surface camera at 70 frames/sec with a 90°



0 0.3 1.0 1.7 2.4

3.1 3.8 4.5 5.2 5.9

Time (msec)

Fig. 43. Cavitation from 25 gm loose tetryl charge 1 ft 3 in. beneath the surface.

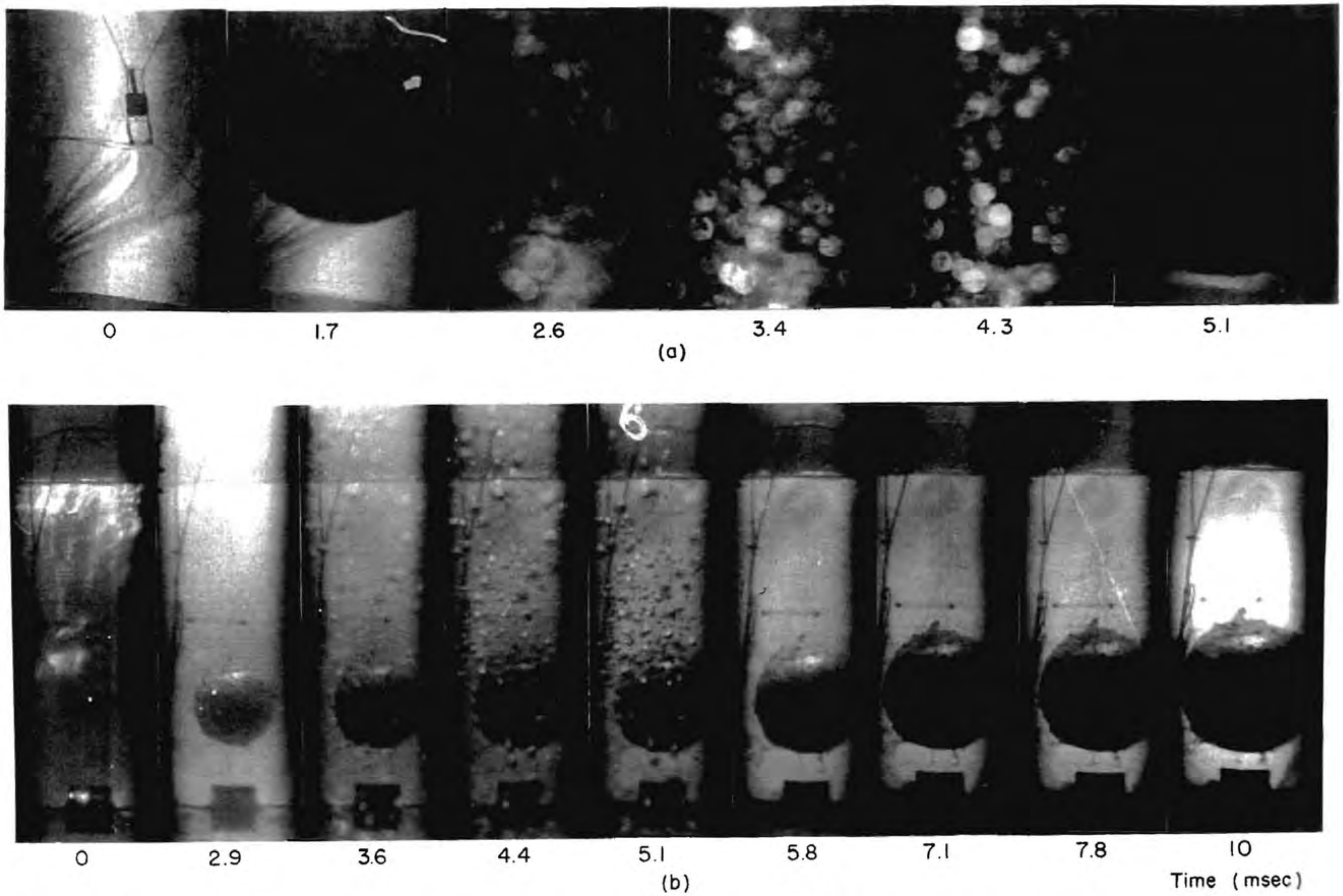


Fig. 44. Cavitation from 25 gm tetryl charges 5 ft beneath surface. (a) Eastman camera. (b) Fastax camera.

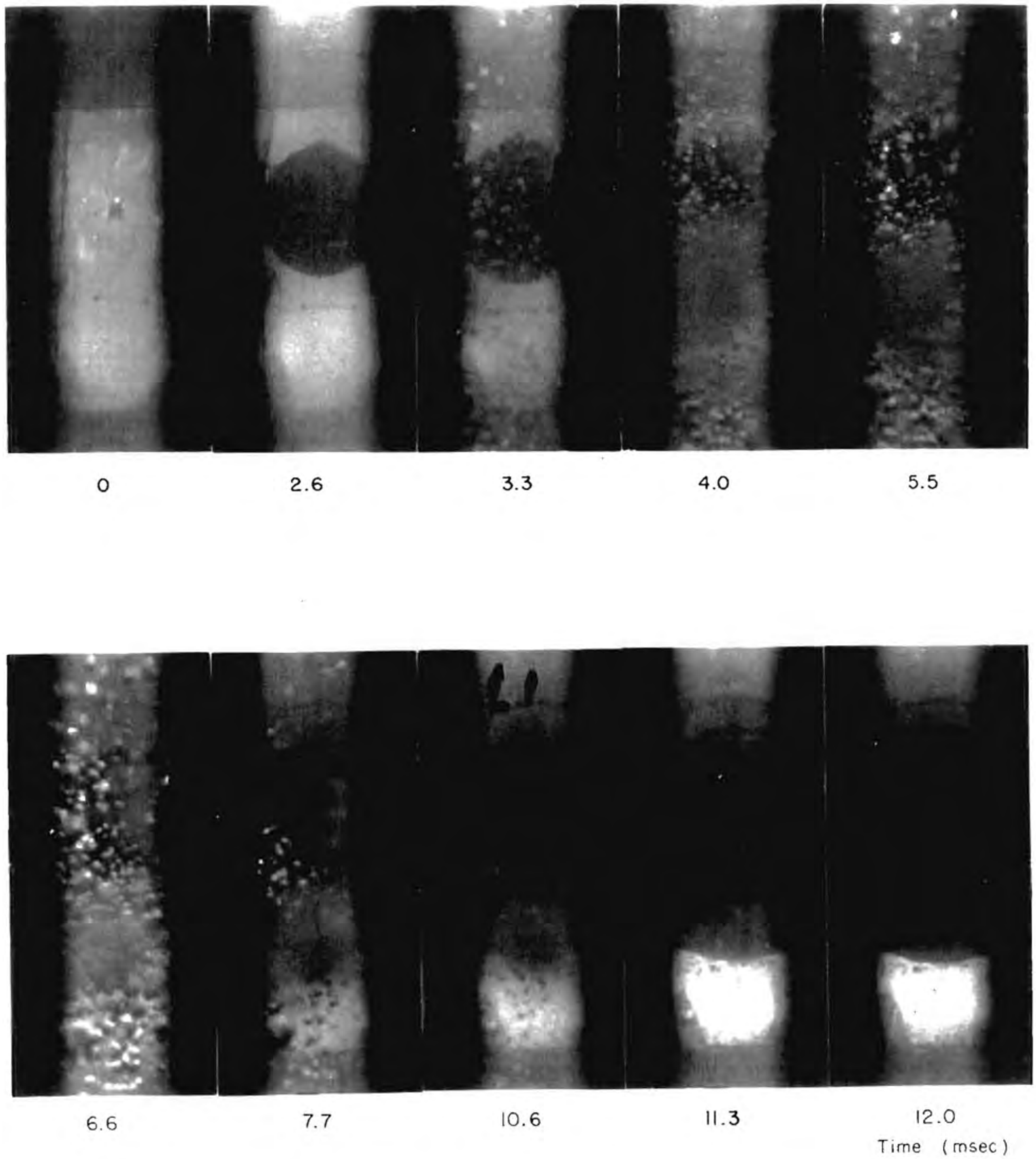


Fig. 45. Cavitation from 1/2 lb torpex charge 4.5 ft beneath surface.

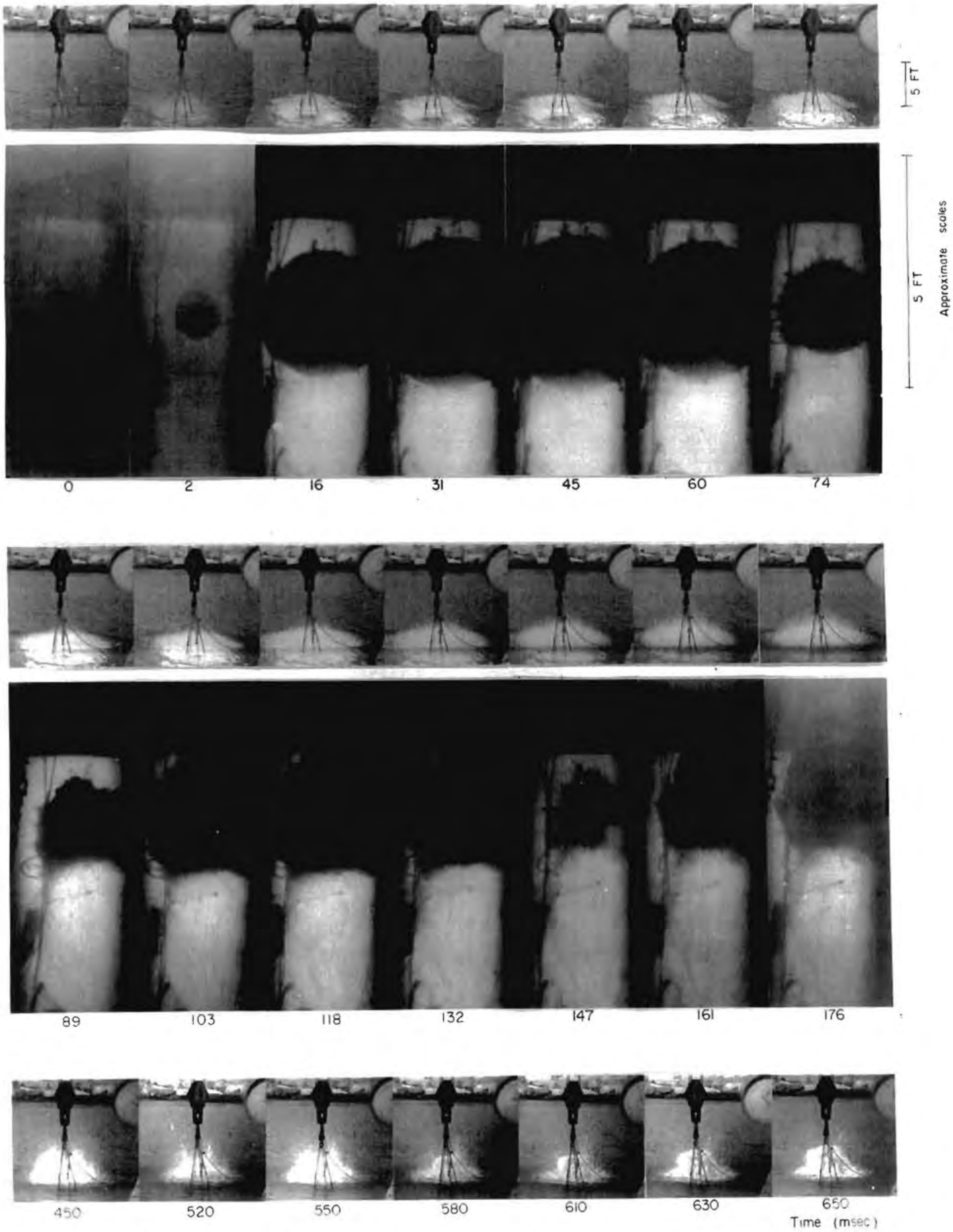


Fig 46 Simultaneous underwater and surface pictures of the explosion of a 25 gm tetryl charge 5 ft beneath the surface

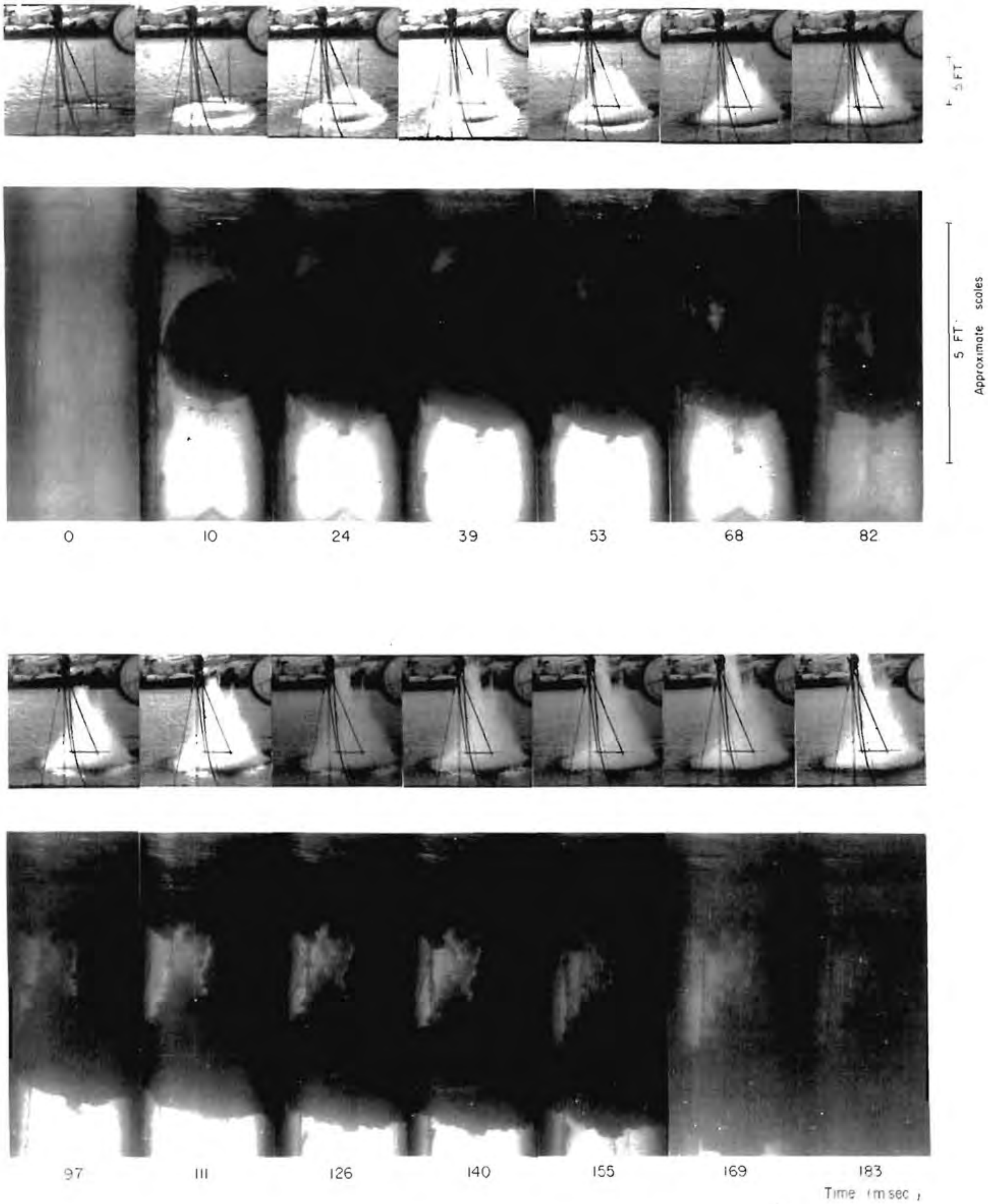


Fig 47 Simultaneous underwater and surface pictures of the explosion of a 25 gm tetryl charge . ft 9 in beneath the surface

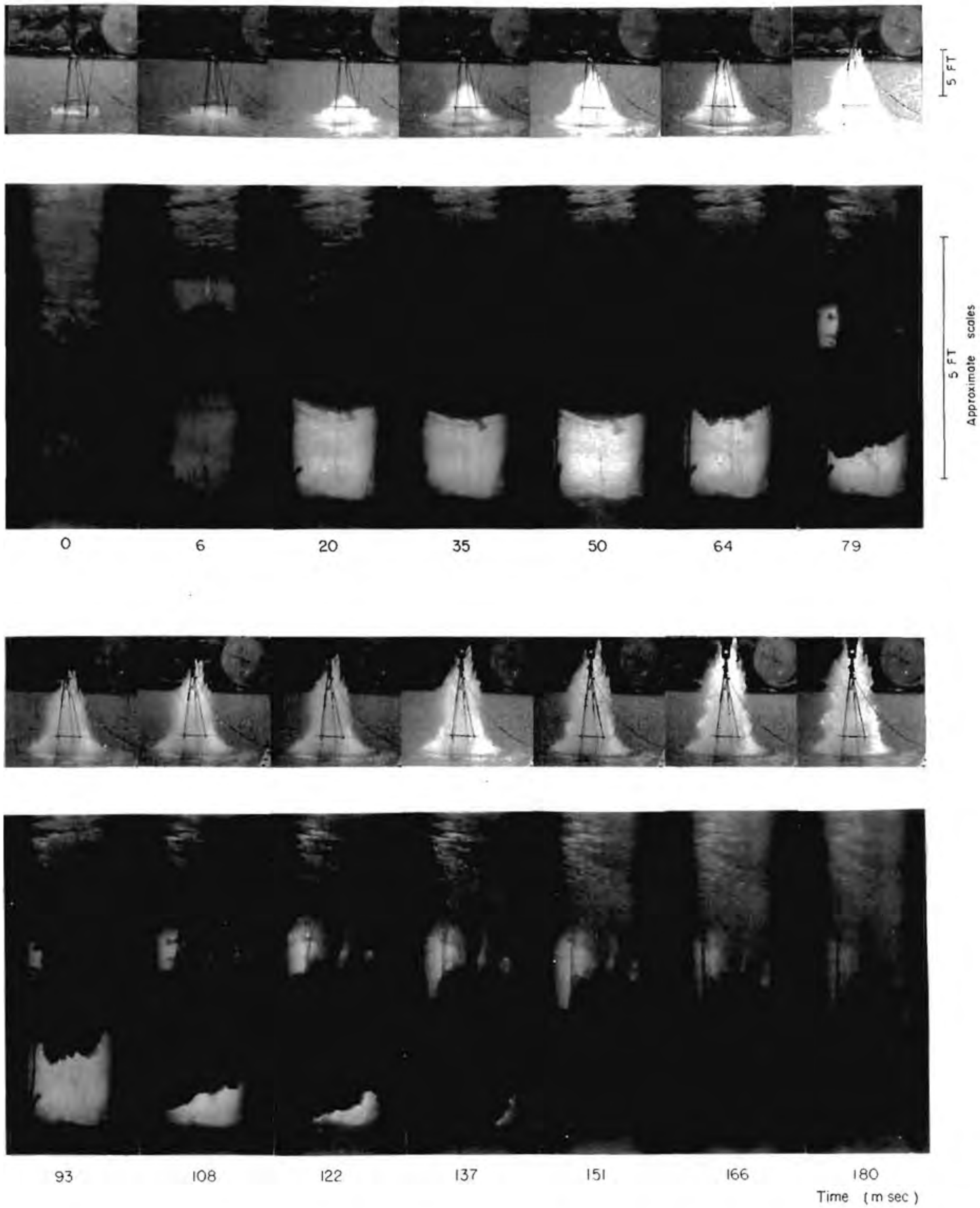


Fig. 48 Simultaneous underwater and surface pictures of the explosion of a 25 gm tetryl charge 1 ft 3 in beneath the surface.

shutter angle; the shutter on the surface camera was thus open for about 3.5 msec, during which time five underwater frames were exposed.

To find the time of the first surface frame after detonation, a rough measurement of the height of the spray dome was made. From the known shock pressure the velocity of rise was calculated and from this and the dome height the approximate time relative to detonation was found.

In Fig. 46 the charge was 5 ft beneath the surface. The first pair of pictures shows the appearance before detonation. The two pictures are not scaled to the same size, as indicated. The surface picture shows the chains supporting the rig, part of the stop watch used for timing, and the shore in the background. Behind the chains and slightly to the right a vertical piece of iron rod indicates the approximate position of the charge. This rod is an extension of the right hand side of the frame visible in the underwater picture supporting the charge.

In the second frame, the effects of firing the charge are seen from above as a haze on the surface--the beginning of the spray dome--and a white patch in the foreground caused by light from the flash bulbs. In the succeeding frames the building up of the spray dome may be followed and at 160-170 msec the fading out of the light from the second set of flash bulbs may be seen. Frame 15 shows the spray dome at 450 msec, long after the film in the underwater camera has run out. The fine vertical jets of spray seen earlier are missing and the dome is falling. Still later, the bubble, which has lost all of its oscillation energy by this time, breaks through the surface. The remaining frames show the continuation of this process.

Figure 47 shows a similar series of pictures of a charge which was somewhat closer to the surface, but still below venting depth. In this case there is a much more rapid rise of the spray dome which continues throughout the pictures shown. The dome width is less in this case than at the 5 ft depth.

On this shot the second set of photoflash bulbs did not come on until the first set was completely out, leaving a gap of 20-30 msec where there was no artificial illumination. This may be seen in both pictures taken at 82 msec after detonation. The illumination from the second set of bulbs which appears in the next frame seems to be unevenly distributed.

In Fig. 48 the charge was at 1 ft 3 in.--venting depth. The bubble may be seen breaking through the surface in the underwater picture taken at 35 msec, although no evidence of this is apparent in the surface picture. As a possible result, however, spray jets in the edge of the plume are oriented at a slight angle away from the vertical. In the last few frames the result of this sidewards motion becomes more evident at the edges of the plume about $\frac{1}{4}$ of the way up. The spray dome seems to be still narrower here at its base than in the case at 1 ft 9 in.

APPENDIX I

Time Delay Gain Changers

These units were originally designed for use with piezoelectric gauges and cables, but have found application here for performing a switching action at a preset time after reception of a tripping signal from some external source.

The circuit for these is shown in Fig. 49. The tripping pulse, which must be greater than 1.0 volt, fires the first 2050 thyratron. This changes the next tube, a 6SL7, from full conduction to full cutoff. The timing condenser C then proceeds to charge towards the positive supply potential at a rate determined by the supply voltage and the R·C of the condenser circuit. When the voltage across condenser C reaches approximately 3 volts, the second 2050 thyratron fires. The plate resistance of this 2050 is sufficiently low to permit enough current to pass to energize the three Sigma, Type 4AH, 500 ohm relays in the cathode circuit.

The thyratrons must be manually reset after tripping by opening the lead from the power supply. Ignition of the $\frac{1}{4}$ watt neon bulb connected to the plate of the last thyratron ("Ready Light") indicates that the circuit has been reset in this manner.

By suitable adjustment of the timing condenser C, the time between the trip pulse and the energizing of the relays may be set at times varying between 0.01 and 1.0 secs in intervals of 0.01 sec.

For use in firing circuits the relay circuit has been arranged to make a connection between the input and output circuits, using only one of the three relays shown. This is shown in Figs. 8 and 10 and described in the accompanying text.

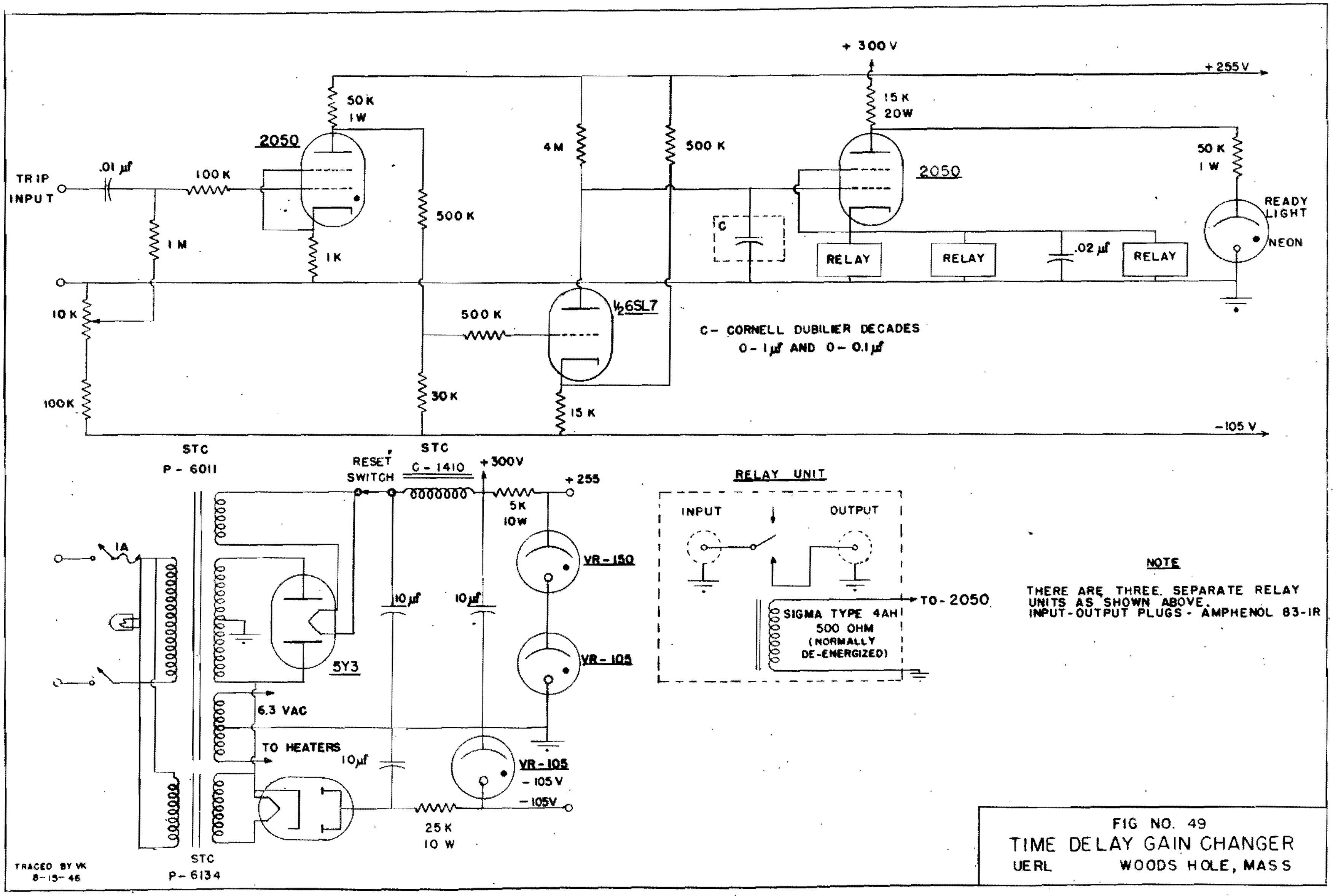


FIG NO. 49
TIME DELAY GAIN CHANGER
UERL WOODS HOLE, MASS

APPENDIX II

UERL Numbers of Shots Shown in Figures*

Figure Number	Shot Number	Figure Number	Shot Number
1	E36	e	G21F
2	G39E	f	G125F
3	GC101F	34	E20
4	GC150F	35	E35
16	G16F	36	G135F
17	G4F	37	G145F
18	G7F	38	G144F
19	G7F	39	G151F
20	G15F	40a	G135F
21	G109J	b	G145F
22	G71F	c	G144F
23	G19F	d	G151F
24	G148F	41a	G136F
25	G22F	b	G146F
26	G110J	c	G135F
27	G117J	42	G143F
28	G75F	43	G149F
29	G109J	44a	G81E
30	G33F	b	G150F
32	G77F	45	G142F
33a	G8F	46	G147F
b	G118F	47	G132F
c	G9F	48	G149F
d	G126F		

* Note: The shot numbers with an E were taken with the Eastman High-Speed camera, those with an F with the Fastax camera, and those with a J with the Jerome camera.

Distribution List

Chief of the Bureau of Ordnance (Ad6c) Copy Nos. 1-20
Chief of the Bureau of Ships, Copy Nos. 21-23
Chief of the Bureau of Aeronautics, Copy Nos. 24-25
Chief of the Office of Naval Research, Copy Nos. 26-27
CO, Naval Ordnance Test Station, Inyokern, Calif., Copy No. 28
CO, Naval Proving Ground, Dahlgren, Va., Copy No. 29
CO, Naval Mine Warfare Test Station, Solomons, Maryland, Copy No. 30
OinC, Naval Ordnance Laboratory, Naval Gun Factory, Washington, D. C., Copy Nos. 31-34
Director, David Taylor Model Basin, Carderock, Md., Copy Nos. 35-36
ChOrd, War Department, Washington, D. C., Copy Nos. 37-38
Director, Woods Hole Oceanographic Institution, Woods Hole, Mass., Copy No. 39
Director, Underwater Explosives Research Laboratory, Woods Hole, Mass., Copy Nos. 40-49
Director, Applied Mathematics Panel, New York University, 53 Washington Square South, New York, N. Y., Copy No. 50
Director, British Commonwealth Scientific Office, 1785 Mass. Ave., Washington, D. C., Copy Nos. 51-53
Director, Scripps Institute of Oceanography, La Jolla, Calif., Copy No. 54
Chief of the Bureau of Ordnance (Rec) Copy Nos 55-70